Calhoun
Institutional Archive of the Naval Postgraduate School

Calhoun: The NPS Institutional Archive

DSpace Repository

Theses and Dissertations 1. Thesis and Dissertation Collection, all items

1939-05

Composition of exhaust gases of solid injection pre-combustion chamber diesel engine with reduced air charge.

Ramsbotham, Robert Joynson

University of California

---

http://hdl.handle.net/10945/6349

This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States.

Downloaded from NPS Archive: Calhoun

DUDLEY KNOX LIBRARY

Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

http://www.nps.edu/library

COMPOSITION OF EXHAUST GASES OF SOLID INJECTION PRE-COMBUSTION CHAMBER DIESEL ENGINE WITH REDUCED AIR CHARGE.

BY

Robert Joynson Ramsbotham

Thesis
R2

COMPOSITION OF EXHAUST GASES OF SOLID INJECTION PRE-COMBUSTION CHAMBER DIESEL ENGINE WITH REDUCED AIR CHARGE

By

Robert Joynson Ramsbotham
Grad. (United States Naval Academy) 1929

THESIS

Submitted in partial satisfaction of the requirements
for the degree

of

MASTER OF SCIENCE

in

Mechanical Engineering

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA

Carl J. Vogt, M.S.

Merle Randall, Ph.D.

Emil E. Weibel, Ph.D.

Committee in Charge

15 May 1939

INTRODUCTION:

The exhaust of a Diesel engine may contain various amounts of carbon dioxide, oxygen, carbon monoxide, nitrogen, water vapor, sulfur dioxide, hydrogen, and methane. The amount of each constituent depends upon the conditions of operation in each case; such as: (a) the type of engine; (b) the type of combustion; (c) the speed; (d) the load; (e) the fuel and (f) the amount of air supplied. Several methods have been used to determine the air to fuel ratio at which the engine is operating and the degree of incomplete combustion from the percentages of the various constituents of the exhaust gases. In making an analysis of the exhaust gases for such a purpose by the methods illustrated in references (b) and (c) the amount of water vapor cannot be determined because of the water present in the apparatus. Similarly the amount of sulfur dioxide cannot be determined by these methods and is assumed to be absorbed by the liquid in the apparatus. Maleev, reference (c), used a method based upon the amounts of carbon dioxide, oxygen, carbon monoxide, nitrogen, hydrogen, and methane. This method, however, has the disadvantage of requiring laboratory apparatus too elaborate for field use. Gerrish and Tessman, reference (b), using the same exhaust gas analysis apparatus, found that the amounts of hydrogen and methane were small and related to the amount of carbon monoxide. Therefore, the important constituents

6317

are carbon dioxide, oxygen, and carbon monoxide, since the amount of nitrogen can be computed from these. The percentages by volume of carbon dioxide, oxygen, and carbon monoxide in the exhaust gases can be found with the Orsat apparatus. Two methods of determining the air to fuel ratio and degree of incomplete combustion from the carbon dioxide and oxygen in the exhaust gases are the Ackermann, reference (a), and the Ostwald, reference (b), Combustion Triangles.

The Ostwald Combustion Triangle is a diagram showing the percentages by volume of carbon dioxide, oxygen, and carbon monoxide in the gases resulting from the combustion of a definite fuel with various quantities of air. Thus, with known percentages of carbon dioxide and oxygen the excess air factor and the percentage of carbon monoxide can be found from the Ostwald triangle. The theoretical minimum pounds of air required for complete combustion of one pound fuel multiplied by the excess air factor gives the air to fuel ratio, pounds of air per pound of fuel. The Ostwald triangle has been used with success to determine both the air to fuel ratio and the percentage of carbon monoxide with engines operating on the Otto cycle, reference (b). It has been used successfully also with Diesel engines, references (b) and (g). Figure 1 is a typical Ostwald Combustion Triangle.

The Ostwald Combustion Triangle is based upon the assumption that incomplete combustion results in the formation of carbon monoxide. It has been found, however, that in many cases incomplete combustion takes place in Diesel engines with high percentages of excess air without the formation of carbon monoxide. In these cases soot instead of carbon monoxide was found in the exhaust gases, reference (a). For this reason Dr. Ing. G. Ackermann formulated a combustion triangle based upon the assumption that soot and not carbon monoxide results from incomplete combustion, reference (a). The Ostwald and Ackermann triangles are similar in that both use the percentages by volume of carbon dioxide and oxygen in the exhaust gases to indicate the excess air factor and thus the air to fuel ratio. The Ackermann triangle for given percentages of carbon dioxide and oxygen also indicates the amount of soot as unburned carbon, a fraction of the carbon in the fuel, instead of the percentage of carbon monoxide. Figure 2 is a typical Ackermann Combustion Triangle.

Both the Ostwald and Ackermann triangles are based upon the approximate analysis of the fuel being used, particularly the parts by weight of hydrogen and carbon and the resultant h/c ratio. Unfortunately the manufacturers selling fuel for Diesel engines do not furnish this analysis and in many cases do not even make such an analysis. Therefore a Diesel engine operator in order to use either combustion triangle is forced either to have an analysis made of his fuel or to assume that an analysis given in reference tables is that of his fuel.

Therefore, in view of the above questions facing the Diesel engine operator, tests were made on a 4 cycle, 4 cylinder, solid injection, pre-combustion chamber Caterpillar engine of a standard commercial design to determine the following:

1. The percentages by volume of carbon dioxide, oxygen and carbon monoxide in the exhaust gases.

2. The relative merits of the Ostwald and Ackermann combustion triangles.

3. The variation in the results obtained with the Ostwald and Ackermann diagrams when the exact analysis of the fuel is not known.

APPARATUS:

A. Diesel Engine

Caterpillar D4400; 4 cylinder; 4 cycle; solid injection; pre-combustion chamber. Bore 4.5 in.; stroke 5.5 in.; power, 44 BHP at 1400 RPM.

B. Load

Sprague Electric Dynamometer.
50 HP; speed 1650-3000 RPM.

C. Speed Measurement

Electrically operated counter and clock.

D. Fuel Measurement

195.5 m.l. burette connected to fuel system by three-way valve; copper Constantan thermocouple.

E. Air Measurement

Bell mouth orifice, diameter 1.5 in.; differential draft gauge.

F. Exhaust Gas Analysis

Water aspirator; Orsat apparatus.

PROCEDURE:

A. General:

At the beginning of each day's operation the engine was started and allowed to warm up, first with no load and then under load until steady operating conditions of temperature and oil pressure were reached. The fuel pump throttle lever of the engine, 3 in Figure 5, was then set to give the desired speed. The dynamometer was adjusted to give the required load. The air intake valve, 4 in Figure 4, was set for the approximate drop across the air orifice, 3 Figure 4, previously computed for the desired air change, as indicated by the draft gauge, 5 Figure 4. Since throttling the air supply reduced both the speed and the output of the engine, it was then necessary to rebalance the load by adjusting the rheostats of the dynamometer and to increase the speed by changing the position of the fuel lever. When a balance had been obtained the engine was allowed to run for several minutes before data were taken. During the time taken for the fuel consumption measurement an exhaust gas sample was obtained for analysis. The above procedure was repeated for different loads, speeds, and air charges.

B. Fuel Measurement:

The time and revolutions for the consumption of 195.5 milliliters of fuel were obtained by the operation of the electrically controlled clock and revolution counter in conjunction with the 195.5 m.l. burette, 1 Figure 5, and three-way valve, 2 Figure 5. The fuel temperature was measured with a copper-constantan thermocouple. The weight of fuel consumed in pounds was computed with the aid of a specific gravity vs. temperature curve.

C. Air Measurement:

The barometric pressure was obtained from a standard mercury barometer in the laboratory. The wet and dry bulb temperatures were taken with a sling psychrometer in the vicinity of the engine. From these the specific humidity was computed by the method of W. H. Carrier and C. O. Mackey, reference (d). With the specific humidity the gas constant, R, was computed by the method of Zerban, reference (e). The specific humidity was also used to compute the pounds of dry air per pound of mixture. The air temperature just before the orifice was obtained with a mercury thermometer. The pressure drop across the orifice was measured by a differential draft gauge. The temperature of the draft gauge fluid was measured and its specific gravity found. The pressure drop in inches of water was then computed. The above data were used to obtain the pounds of dry air per minute.

D. Exhaust Gas Analysis:

In order to obtain a representative sample of exhaust gas from all four cylinders, the sample was taken from the mid point of the exhaust manifold, near the vertical riser connecting the manifold to the exhaust pipe, 1 Figure 4. A water aspirator, 2 Figure 3, was used to aid in removing the sample. To avoid the absorption of carbon-dioxide by water the aspirator was not used as a storage tank, but instead the sample was transferred immediately to the Orsat apparatus, 1 Figure 3, and the analysis made as soon as possible. The primary function of the aspirator tank was that of a mixing chamber to insure a representative sample from all four cylinders. The Orsat was used in the normal fashion, passes in each pipette being continued until two consecutive measurements were the same. Likewise several samples were analyzed for each run until two consecutive samples gave consistent results. Precautions were taken to avoid contamination of samples by sweeping out the Orsat and aspirator tank. The line from the engine to the analysis apparatus was kept swept out between analyses by permitting the exhaust gases to blow through it to the atmosphere.

DISCUSSION:

When using either the Ostwald or Ackermann combustion triangle with a Diesel engine, it must be remembered that engines differ in many respects and that the results obtained with one engine will not necessarily hold for all engines. For instance, a Diesel engine may have either air or solid injection and may or may not have a pre-combustion chamber. Therefore the results found with this particular engine and presented in this discussion may not be general for all Diesel engines.

The tests were conducted at various speeds from 700 to 1400 RPM and with various loads as represented by brake mean effective pressures (BMEP) from 15 to 60 pounds per square inch. Unfortunately no apparatus was available to measure the amount of soot in the exhaust. However, the exhaust pipe supplied ample evidence that soot was present in appreciable amounts. Therefore, the comparison of the Ostwald and Ackermann triangles was based upon the amount of carbon monoxide found with the Orsat and the agreement of the air to fuel ratio as computed to that actually measured. About one hundred runs were made at various loads and speeds over a range of air to fuel ratios from 14.4 to 1 to 61.5 to 1 (pounds of air per pound of fuel).

Ostwald and Ackermann combustion triangles were constructed for eight different fuels described in Table 1. The

choice of these fuels was based upon their approximate analyses being representative of those of possible Diesel fuels. The hydrogen to carbon ratios of these fuels varied from .129 to .1935. Only one fuel was actually used in the engine. All references to fuels of various h/c ratios and to a fuel designated by a number pertain to those of Table 1 which were used to construct the different Ostwald and Ackermann combustion triangles.

The percentages by volume of carbon dioxide, oxygen, and carbon monoxide as determined by the Orsat apparatus are shown in Figure 6 as functions of the air to fuel ratio measured. It is to be noted that no carbon monoxide was found until the air to fuel ratio was below 19 to 1 and that as the ratio was decreased below this value the amount of carbon monoxide increased rapidly. In other words, carbon monoxide did not appear until the excess air had been reduced to about 30 per cent. Figure 7 indicates for 1300 RPM and a BMEP of 30 pounds per square inch the percentages by volume of carbon dioxide, oxygen, and carbon monoxide as functions of the air charge efficiency. The latter is indicated as the pounds of dry air per revolution. Curves similar to those of Figure 7 were obtained for other loads and speeds but the charge efficiency range was limited by the engine's failure to maintain the load and speed. No carbon monoxide was found until the air charge had been reduced appreciably. Figure 8 shows the amount of carbon monoxide as a function of charge efficiency at 1300 RPM for various loads as indicated by BMEP in pounds per square inch from 15 to 60. Figure 9 is the same as Figure 8 except that the speed was 900 RPM. It is to be noted that at both speeds carbon monoxide did not appear at a constant air charge. Instead the air charge at which carbon monoxide first appeared increased as the load increased. The fuel pump rack on this engine was controlled by a governor so that for any setting of the fuel lever a constant speed was maintained over the load range. Consequently as the load was increased more fuel was injected. Therefore the air charge in pounds per revolution representing about 30 per cent excess air increased as the load increased.

Figure 10 shows the specific fuel consumption in pounds per brake horse power hour as a function of the percentage by volume of carbon dioxide and oxygen in the exhaust for 1300 RPM at a BMEP of 30 pounds per square inch. Similar curves were obtained for 1300 and 900 RPM at loads from 15 to 60 pounds per square inch BMEP. As the amount of oxygen decreased and the amount of carbon dioxide increased the specific fuel consumption increased. However, no value of either oxygen or carbon dioxide could be found as a criterion of a radical change in specific fuel consumption.

Figures 11 and 12 show the carbon monoxide as indicated by the different Ostwald diagrams as a function of the air to fuel ratio actually measured. On the same figures is shown the actual carbon monoxide found in the exhaust with the Orsat. It is to be noted that the indicated carbon monoxide for all diagrams except one varied over the air to fuel ratio range of 20 to 55. The curves shown in this range in each case are for the average only. All diagrams indicated a rise in the amount of carbon monoxide for air to fuel ratios below 20 and above 55. In every case except one the carbon monoxide indicated was greater than that found. The Ostwald triangle based upon Fuel 6, with the highest h/c ratio of .1935 indicated zero carbon monoxide for air to fuel ratios from 20 to 55 in agreement with that found, but an increase in carbon monoxide above 55. Below an air to fuel ratio of 20 to 1 it also indicated an increase but the values were less than actual. In fact it showed zero carbon monoxide for an air to fuel ratio as low as 17.5 to 1 when carbon monoxide was actually present. For any air to fuel ratio each Ostwald diagram gave a different amount of carbon monoxide since the h/c ratio of the fuel upon which each diagram was based was different.

Figures 13 to 19 inclusive show for each of the eight fuels of Table 1, for which the combustion triangles were constructed, the agreement of three air to fuel ratios obtained from the combustion triangles with the air to fuel ratio measured. One curve, that of the highest air to fuel ratios was obtained from the Ackermann diagram, taking account of the unburned carbon indicated as soot by the triangle. The curve of the lowest ratios was obtained from the Ackermann diagram, ignoring the amount of soot indicated. The curve resulting from the Ostwald diagram shows air to fuel ratios which are approximately the mean of those indicated by the two Ackermann curves. In each case above an air to fuel ratio of 20 to 1, when the amount of soot indicated was considered the Ackermann triangle gave the best agreement within about 2 per cent. The amount of soot indicated was different for each Ackermann diagram depending upon the h/c ratio of the fuel for which the diagram was constructed. The amount of soot indicated would be correct only when the h/c ratio of the fuel for which the diagram was constructed was the same as that of the fuel actually burned in the engine. However, over the air to fuel ratio range from 20 to 61.5 the air to fuel ratio obtained by the Ackermann triangle, considering the amount of soot shown by the triangle, was sufficiently accurate regardless of the h/c ratio of the fuel for which the triangle was constructed. For an air to fuel ratio below 20 to 1, however, each Ackermann triangle indicated practically a constant air to fuel ratio which was higher than that measured. This is to be expected since the Ackermann triangle is based upon the assumption of soot formation alone with no carbon monoxide while carbon monoxide was present for air to fuel ratios below 20 to 1.

Every Ostwald diagram except the one constructed for the fuel with the highest h/c ratio, Fuel 6, h/c = .1935, indicated an air to fuel ratio appreciably less than that measured for air to fuel ratios above 20 to 1. The error increased as the air to fuel ratio increased until above 50 to 1 the Ostwald triangle indicated an approach to a constant ratio. The Ostwald triangle is based upon the presence of CO as an indication of incomplete combustion. For air to fuel ratios above 20 to 1 no CO was found and the Ostwald diagrams indicate complete combustion. It was evident, however, that in this range there was a certain amount of incomplete combustion. The error of the air to fuel ratio obtained from the Ostwald diagrams varied with the h/c ratio of the fuel for which the diagram was constructed. It would be expected that for air to fuel ratios below 20 to 1 where CO was actually found the Ostwald triangle would give air to fuel ratios with good agreement. However, this was the case only for those diagrams constructed for fuels with the higher h/c ratios. All other triangles indicated air to fuel ratios less than those measured. It would appear that even in the air to fuel ratio range where CO exists the Ostwald triangle gives the correct air to fuel ratio only when made for a fuel whose h/c ratio is very close to that of the fuel used in the engine.

The air to fuel ratios obtained from the Ackermann triangles when the unburned carbon indicated was ignored were in every case less than those obtained from the Ostwald diagram and more in error.

Figure 18 shows the results obtained from the Ackermann and Ostwald triangles for the fuel with the highest h/c ratio of .1935, Fuel 6. Again the Ackermann triangle, considering the soot indicated, gave very good agreement for air to fuel ratios above 20 to 1 and a constant air to fuel ratio greater than the actual below 20 to 1. However, for ratios above 20 to 1 both the Ackermann triangle, ignoring soot, and the Ostwald triangle also gave good agreement, especially up to an air to fuel ratio of about 35 to 1. Above an air to fuel ratio of about 50 to 1 both again exhibited a tendency to approach a constant value less than the actual ratio. For air to fuel ratios below 20 to 1 the Ostwald triangle gave excellent agreement. It is to be noted in this case from Figures 20 and 26 that the Ackermann triangle for this fuel indicated no soot for air to fuel ratios between 20 and 50 and the least amount when any was indicated. However, Figure 12 shows that for air to fuel ratios below 20 to 1 the Ostwald triangle for this fuel indicated less CO than that found. One fact concerning this fuel that the figures do not show is that several pairs of measured CO_2 and O_2 which gave good results for the diagrams based upon the other fuels fell outside the combustion triangles for this fuel.

Figures 20 to 24 inclusive show for 1300 RPM and BMEP's of 15, 30, and 40 pounds per square inch the soot indicated by the various Ackermann triangles as a function of the charge efficiency. The latter is again represented by the pounds of dry air per revolution. In each case the soot indicated by the diagram varied seemingly independently of the air charge and the curves drawn are for average values only. For a given air charge, load, speed, and carbon dioxide and oxygen contents the amount of soot indicated was different for each diagram. It is evident that part of the amount of soot indicated is a correction factor for the difference between the h/c ratio for which the triangle was constructed and that of the fuel actually used in the engine.

Figures 25 and 26 show the soot indicated by the various Ackermann triangles as a function of the air to fuel ratio. Again the amounts for each diagram varied and the curves show average values only.

CONCLUSIONS:

The results of the various tests indicated the following for this particular engine:

I. All Speeds, 700 to 1400 RPM; All Loads, BMEP 15 to 60 lb/in^2
  A. Air to Fuel Ratios Greater than 20 to 1
    1. No CO found by Orsat
    2. All Ostwald triangles except that for fuel with greatest h/c ratio indicated CO
    3. Ostwald triangle for fuel with h/c = .1935 indicated no CO

4. All Ackermann triangles when soot indicated was considered gave air to fuel ratios within 2 per cent of correct value regardless of fuel for which constructed.
5. All Ostwald triangles indicated air to fuel ratios too low by more than 2 per cent. Error varied with h/c ratio of fuel for which triangle was constructed. Error increased as air to fuel ratio increased.

B. Air to Fuel Ratios Less than 20 to 1

1. CO present; first appearance at air to fuel ratio of 19 to 1.
2. All Ostwald triangles except that for fuel with greatest h/c ratio indicated slightly more CO than that found.
3. Ostwald triangle for fuel with h/c = .1935 indicated less CO than that found.
4. All Ackermann triangles indicated constant air to fuel ratio greater than actual.
5. All Ostwald diagrams for fuels with high h/c ratios indicated air to fuel ratios within 2 per cent of correct value.
6. Ostwald diagrams for fuels with low h/c ratios indicated air to fuel ratios less than actual by about 5 per cent.

C. Air to Fuel Ratios 14.4/1 to 61.5/1

1. All Ackermann triangles indicated various amounts of soot independent of air to fuel ratio. Amount indicated varied with h/c ratio of fuel for which triangle was constructed.

2. All Ackermann triangles indicated increased soot for both very high and very low air to fuel ratios.

II. 900 and 1300 RPM; All Loads BMEP 15 to 60 lb/in^2

A. Air charge at which CO first appeared not constant, increased as load increased.

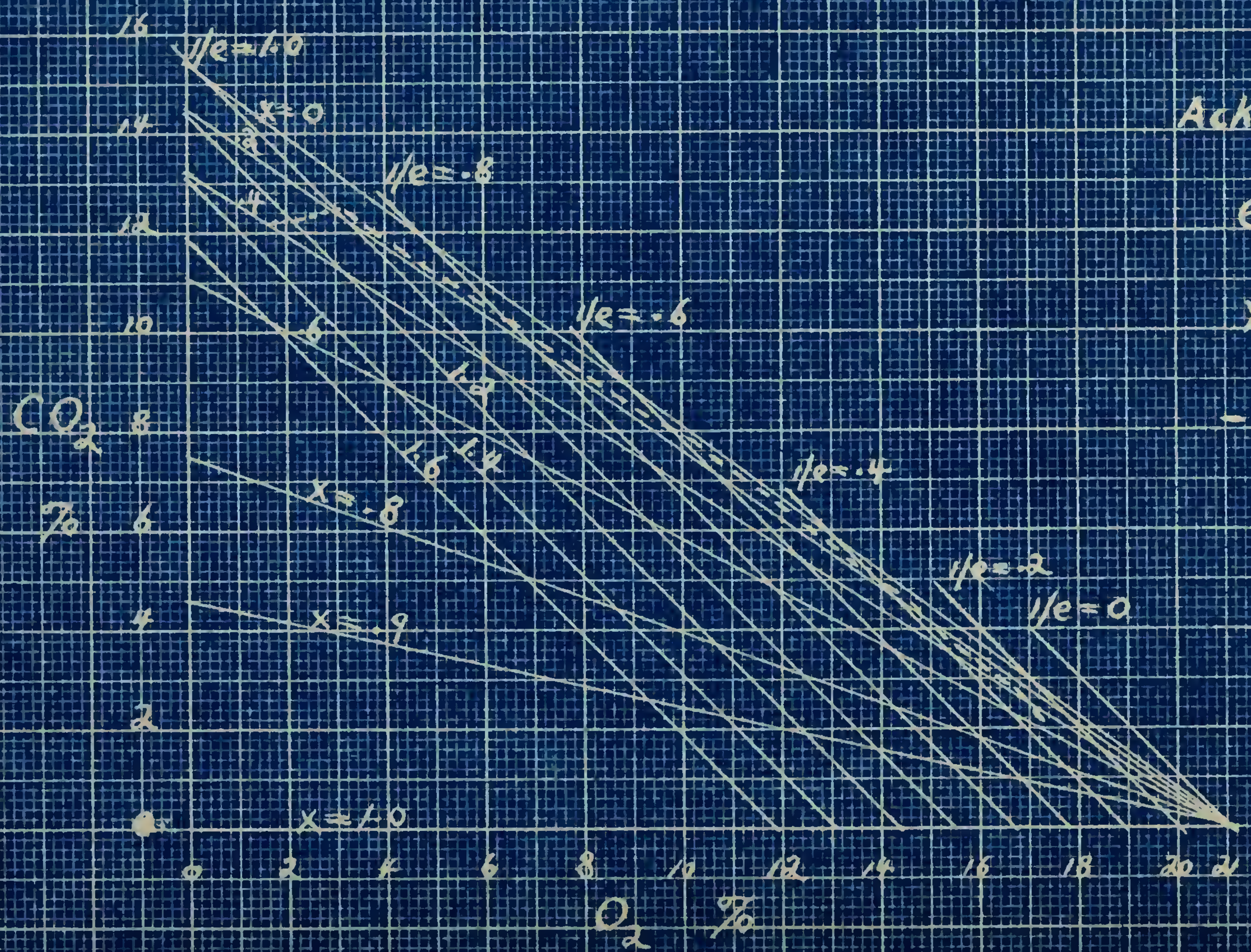


Figure 1

Ackermann Triangle

e = Excess Air Factor

x = Soot = Unburned Carbon

--- Test Results

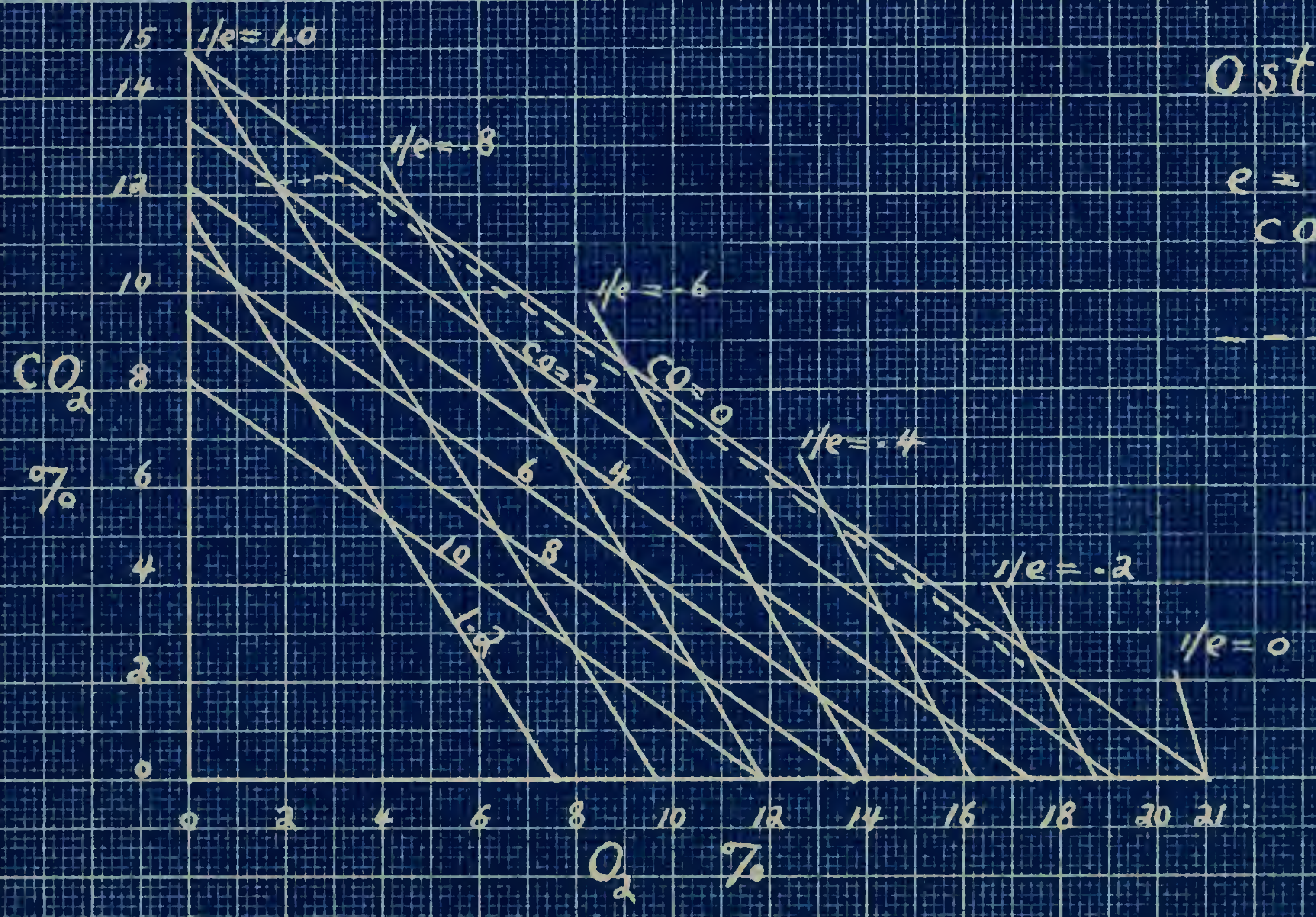
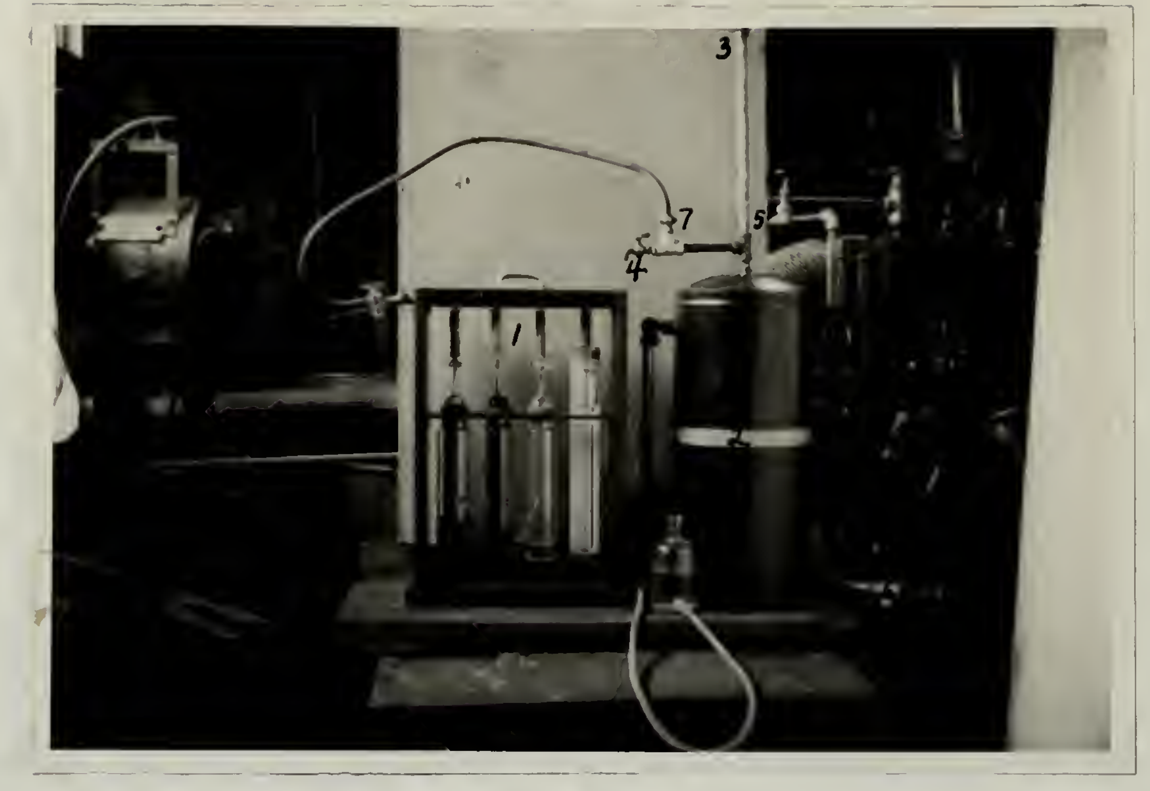


Figure 2

Ostwald Triangle

FIGURE 3

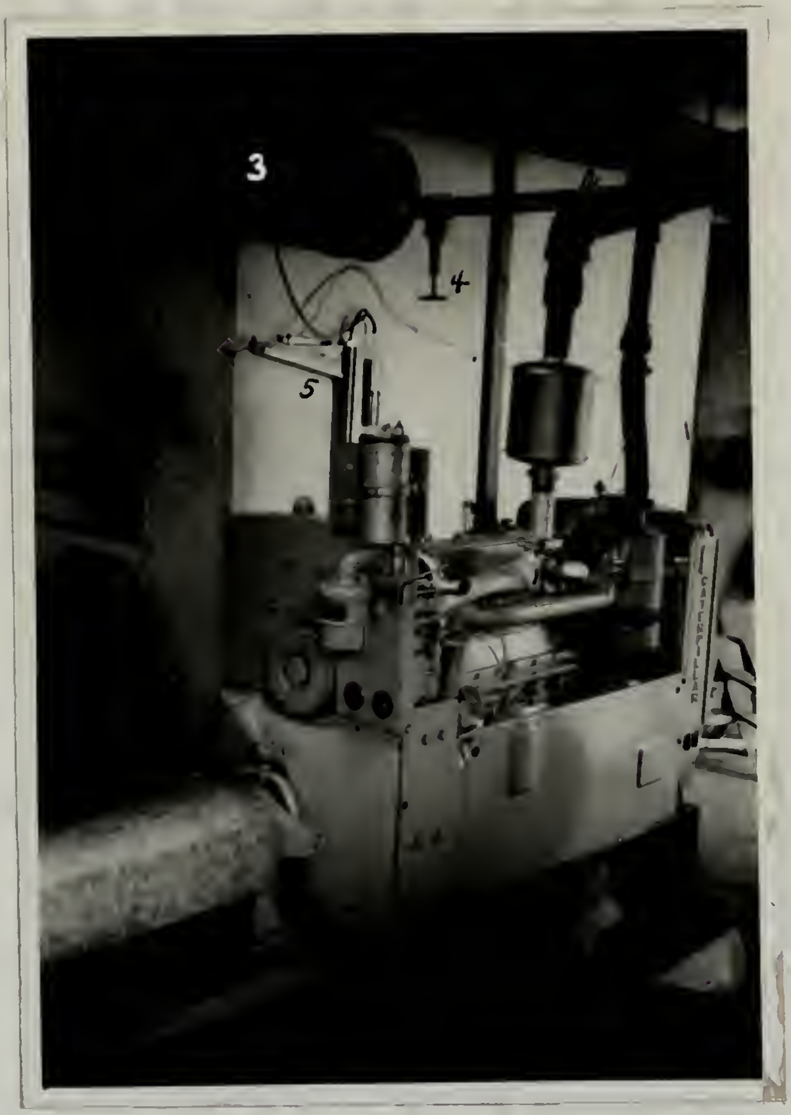
Exhaust Gas Analysis Apparatus



1. Orsat
    - 100 ml. Measuring Burette
    - CO_2 - Caustic Potash
    - O_2 - Pyrogallol
    - CO - Cuprous Chloride
2. Water Aspirator
3. Exhaust from Engine
4. Vent
5. Water Supply
6. Water Drain
7. To Orsat

FIGURE 4

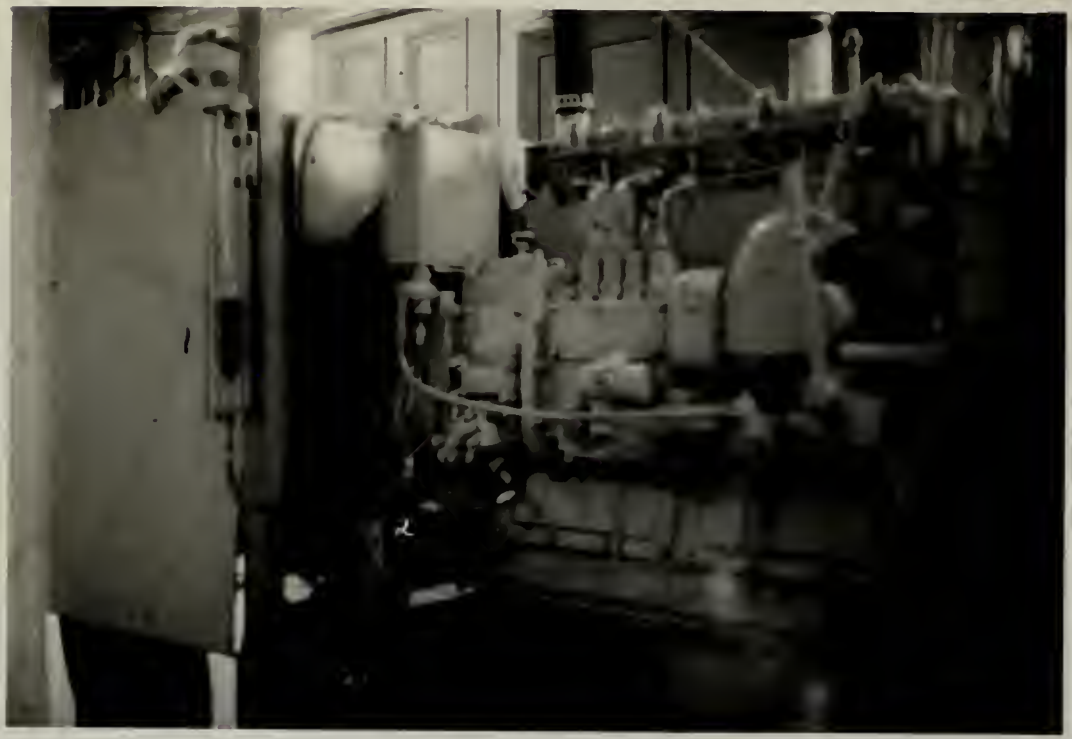
Right Side of Engine Looking Forward



1. Lead to Exhaust Gas Analysis Apparatus
2. Thermocouple for Exhaust Temperature
3. Orifice
4. Air Throttling Valve
5. Draft Gauge

FIGURE 5

Left Side of Engine Looking Forward



1. Fuel Measuring Burette
2. Three Way Fuel Valve
3. Fuel Pump Throttle Lever

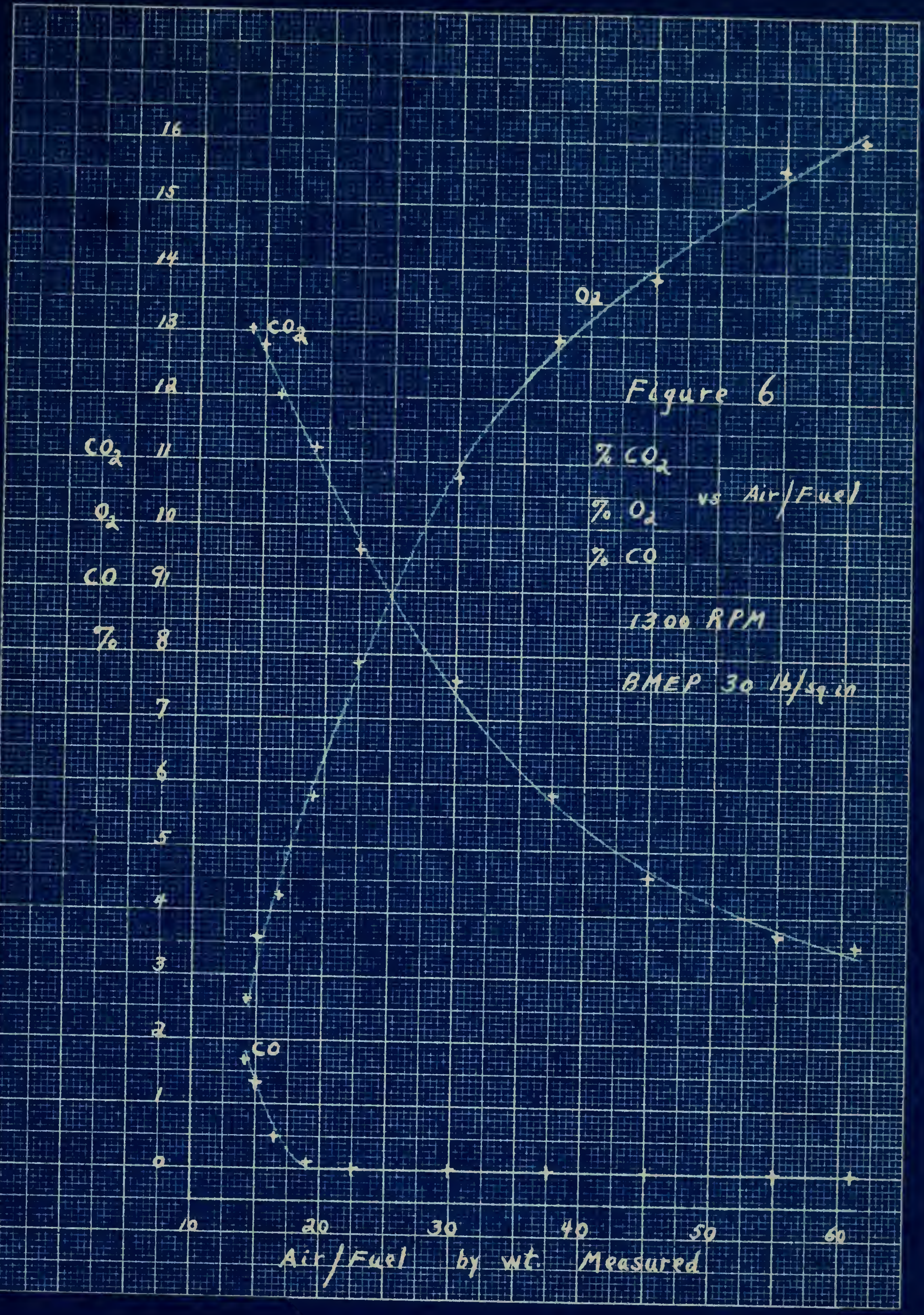


Figure 6

% CO_2

% O_2 vs Air/Fuel

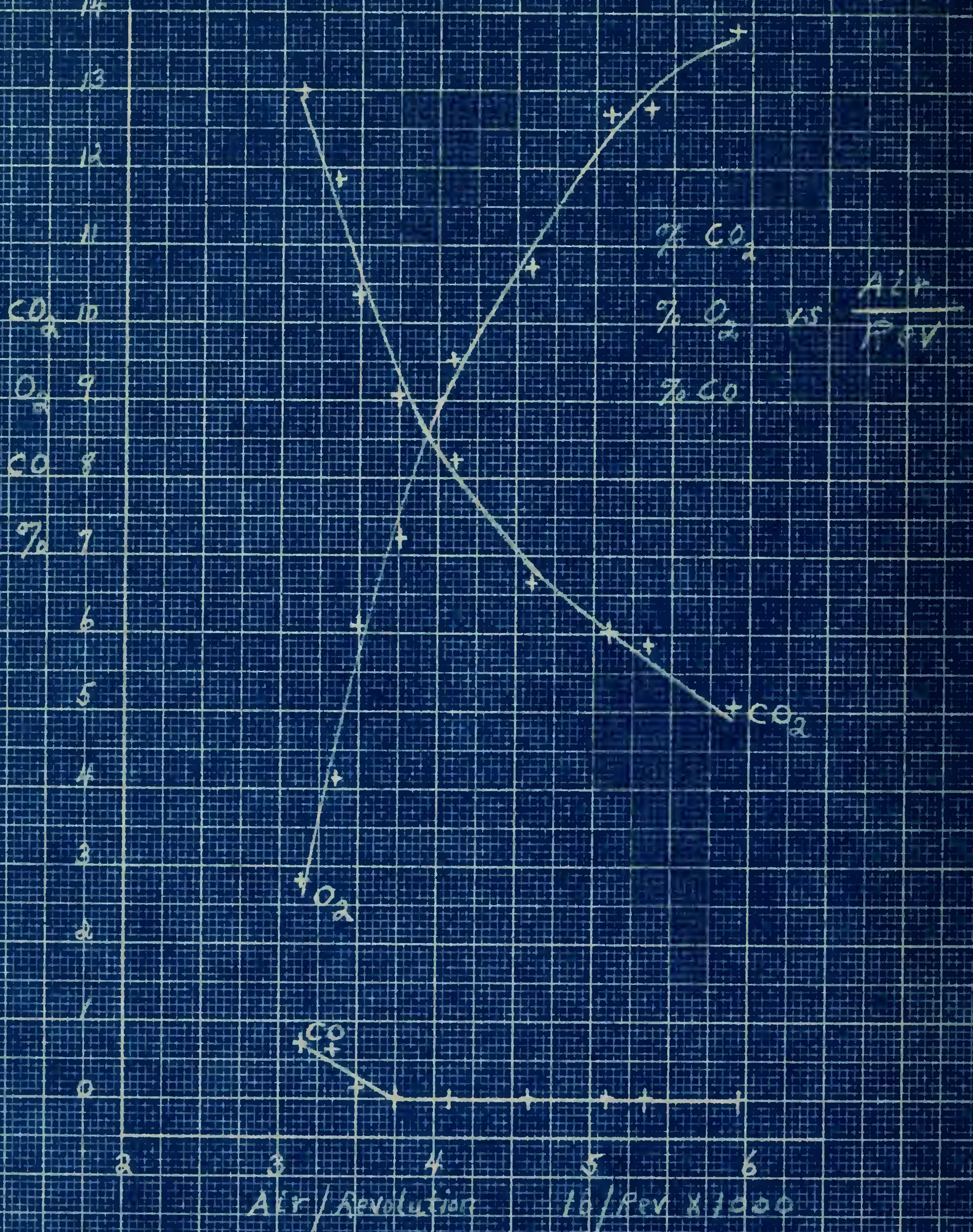
% CO

1300 RPM

BMEP 30 lb/sq.in

Figure 7

1300 RPM BMEP 30 lb/sq in



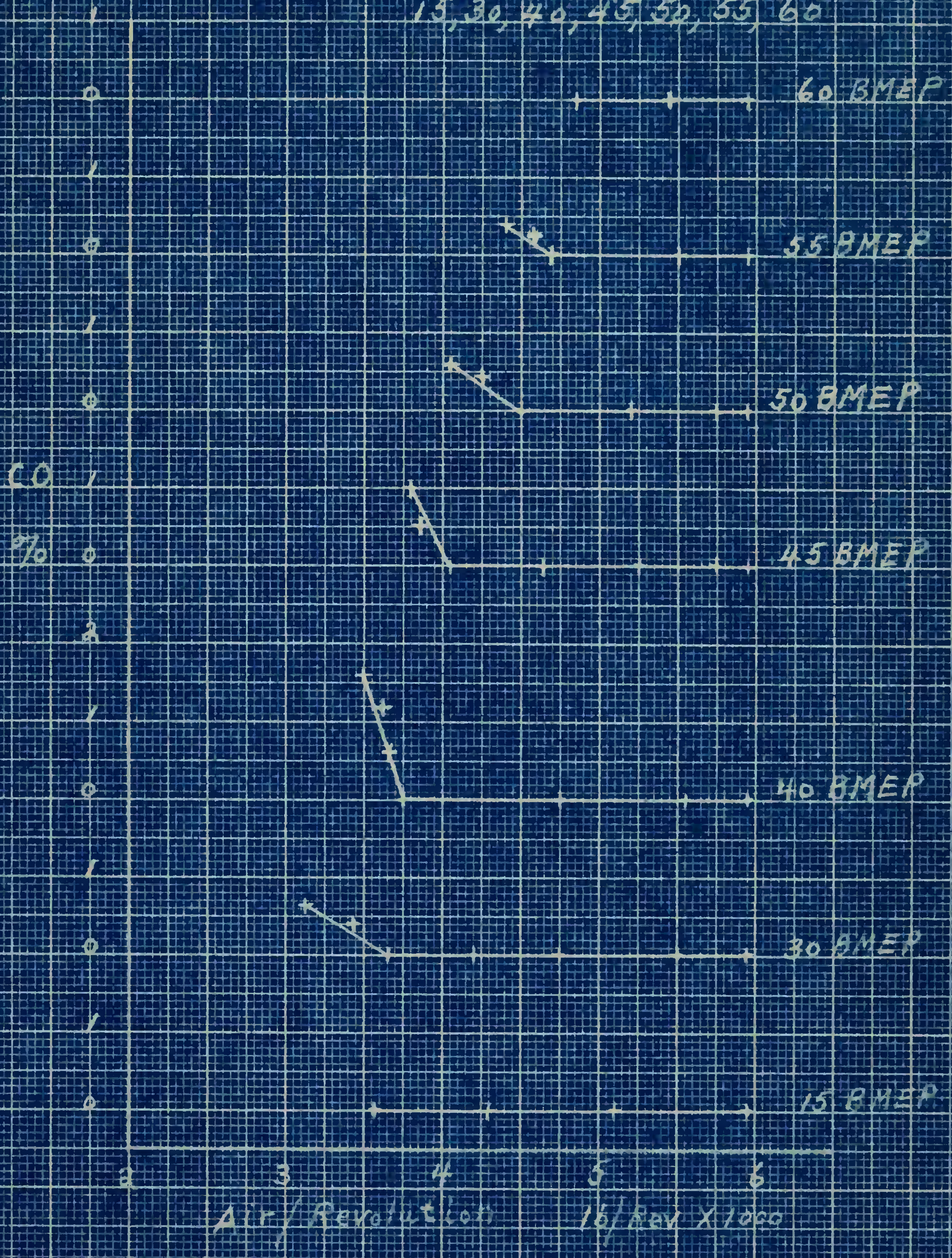


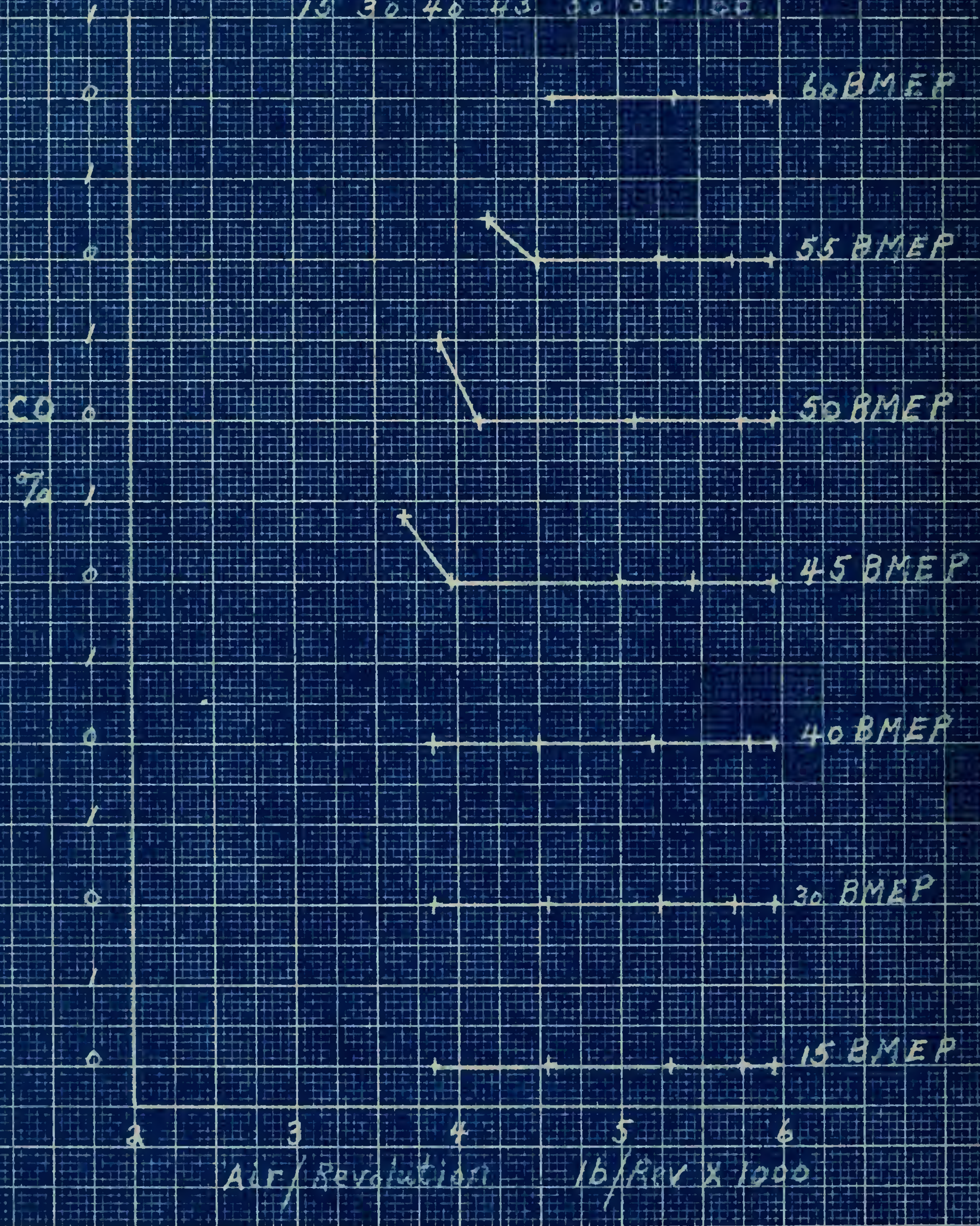
Figure 8

% CO vs Air/Revolution
1300 RPM
BMEP lb/sq in
15, 30, 40, 45, 50, 55, 60

Figure 9

% CO vs Air/Revolution

900 RPM
BMEP lb/sq in
15 30 40 45 50 55 60



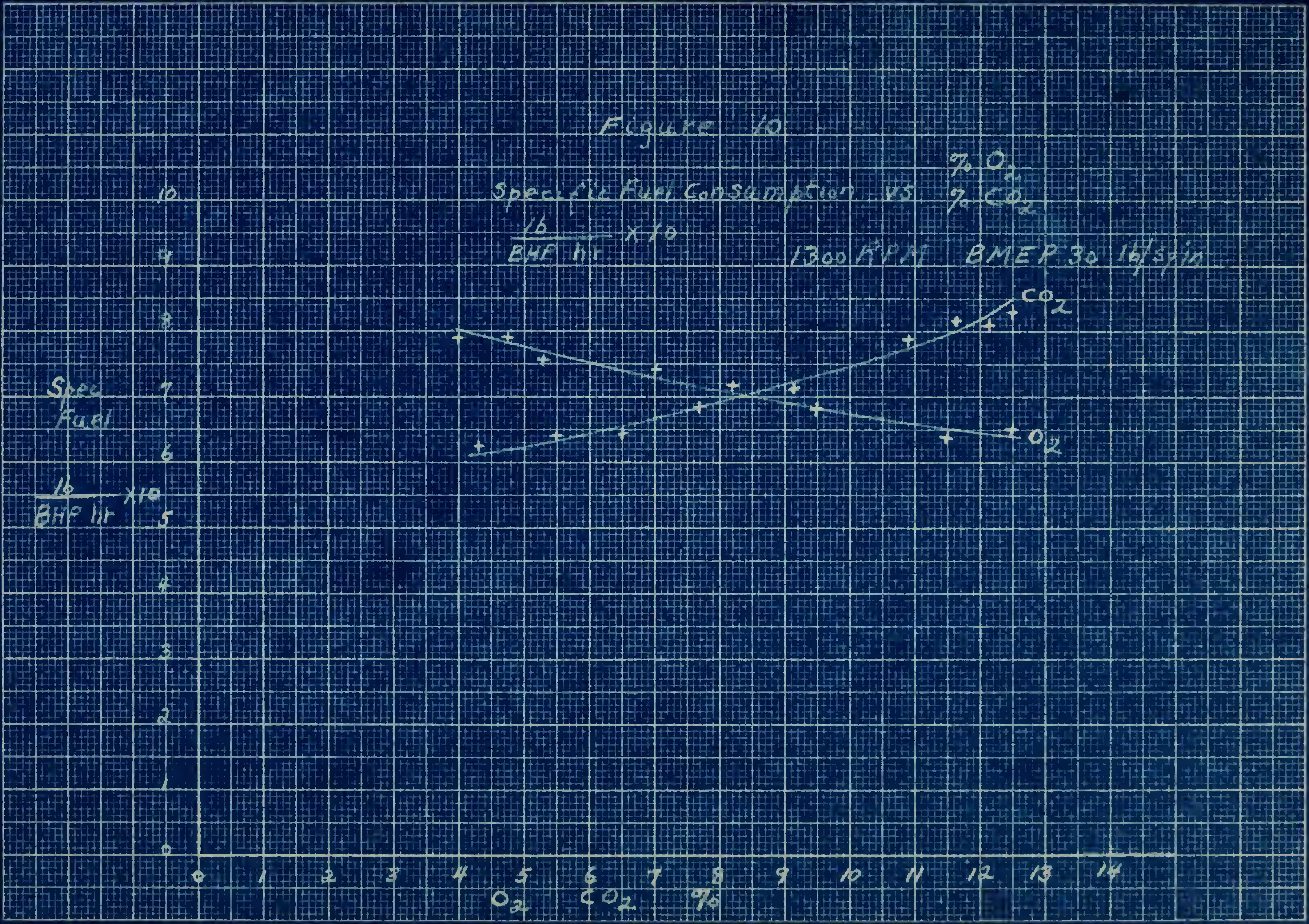


Figure 10

Specific Fuel Consumption vs % O_2 % CO_2

$\frac{lb}{BHP\ hr} \times 10$

1300 RPM BMEP 30 lb/sq in

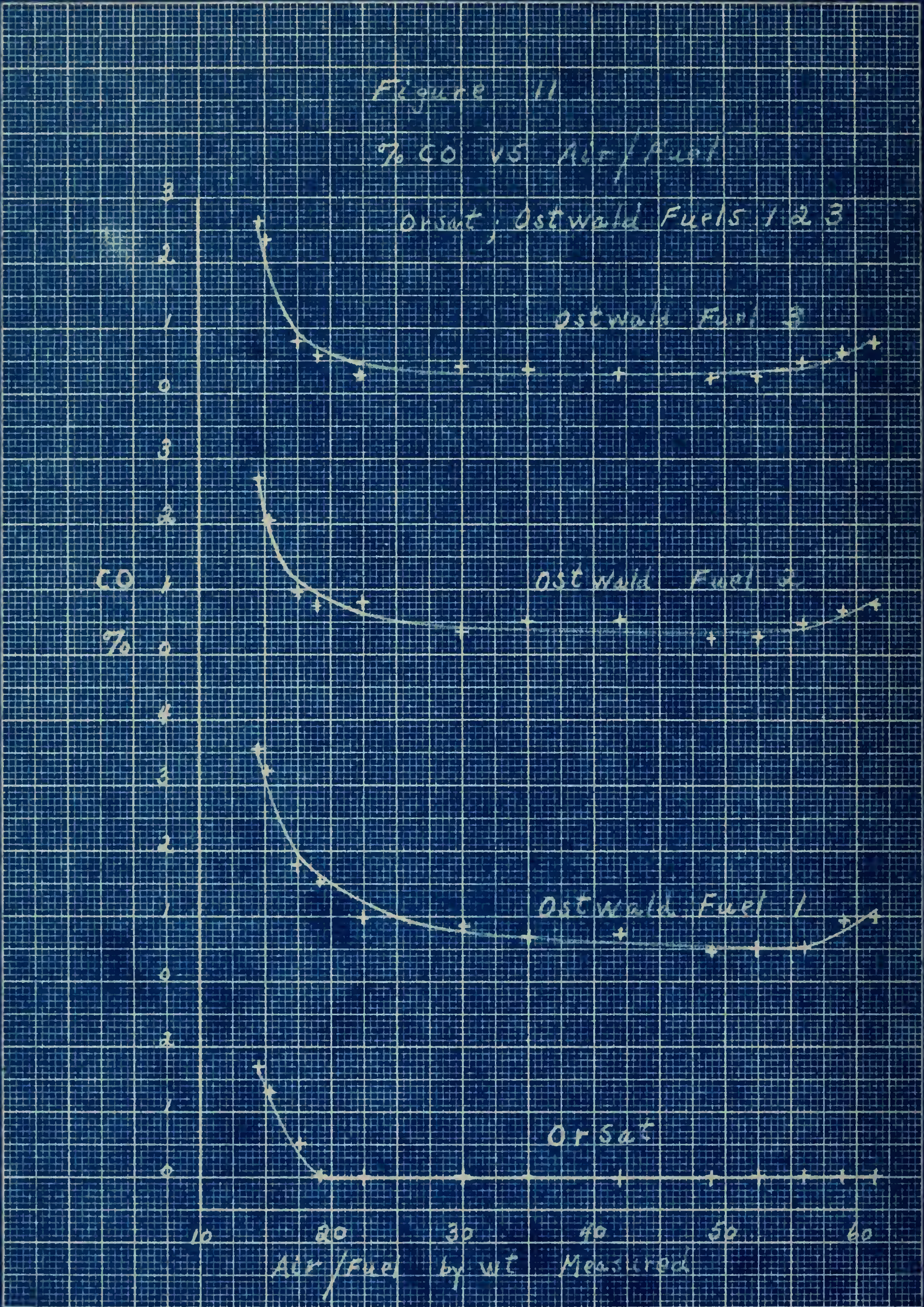


Figure 11

% CO vs Air/Fuel

Orsat; Ostwald Fuels 1 2 3

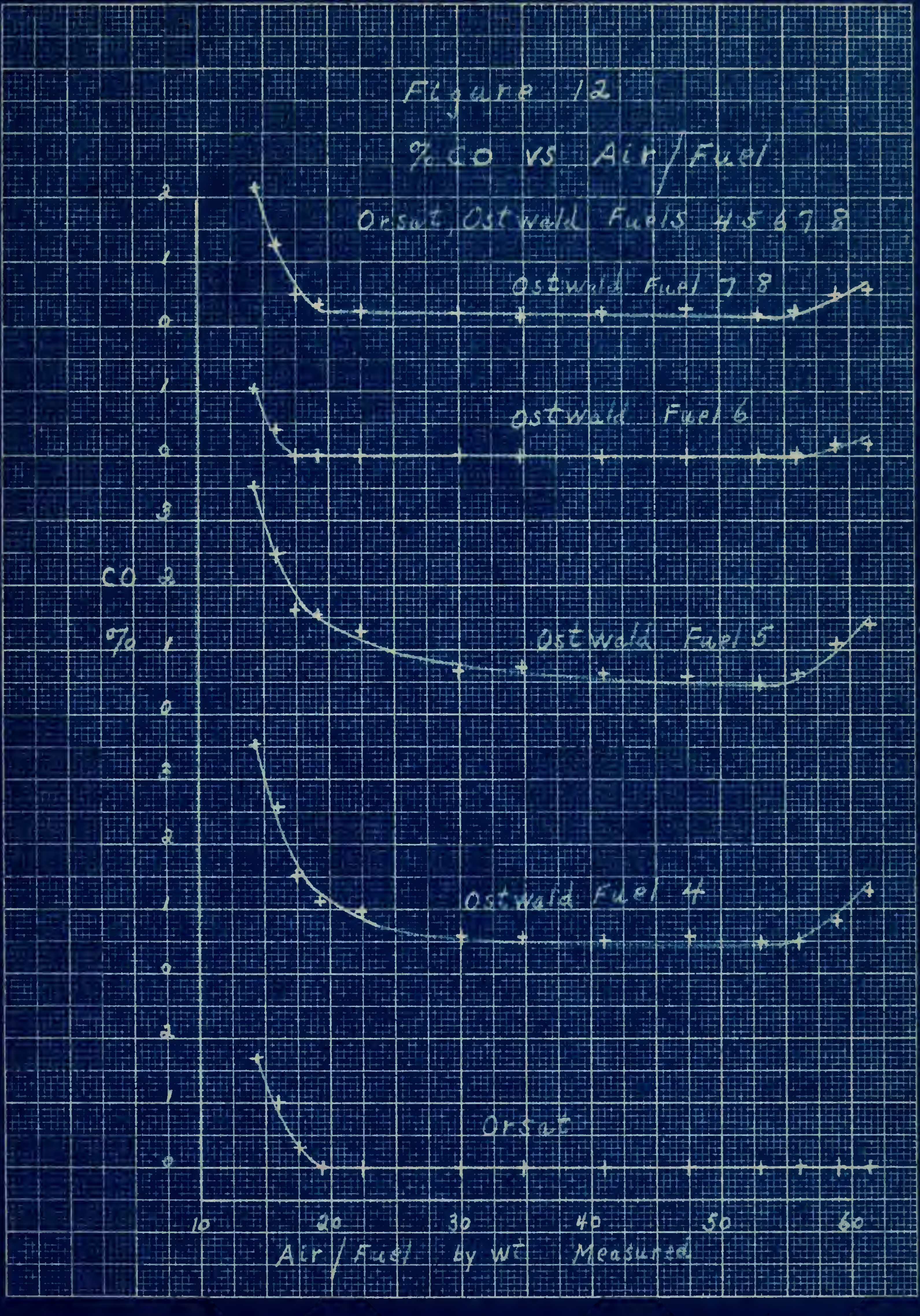
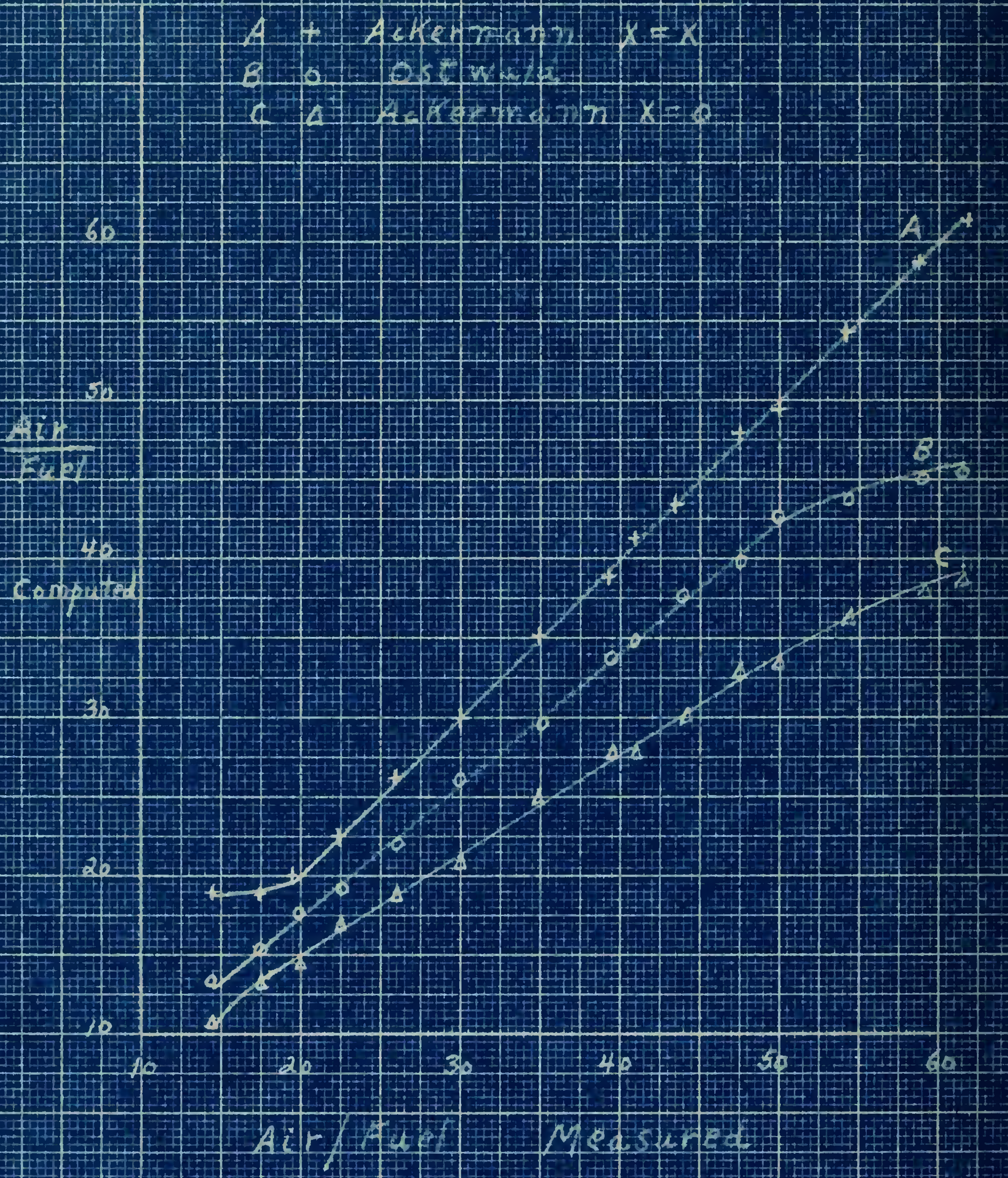


Figure 12
% CO vs Air/Fuel
Orsat, Ostwald Fuels 4 5 6 7 8
Ostwald Fuel 7 8
Ostwald Fuel 6
Ostwald Fuel 5
Ostwald Fuel 4
Orsat
CO
%
2
1
0
1
0
3
2
1
0
3
2
1
0
2
1
0
10
20
30
40
50
60
Air/Fuel by wt Measured

Figure 13

Air/Fuel Computed vs Air/Fuel Measured
Fuel 1 h/c = .132



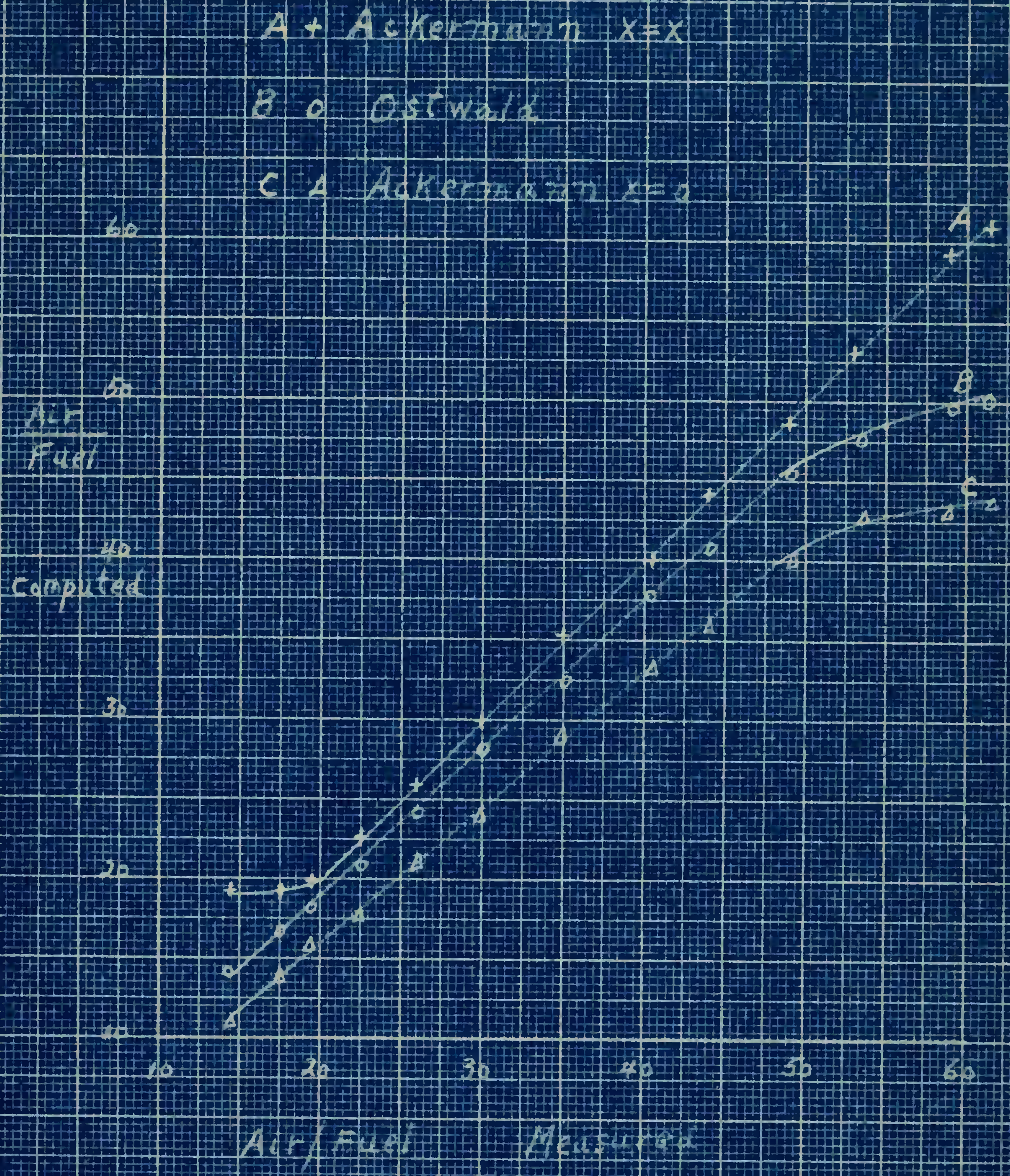


Figure 14

Air/Fuel Computed vs Air/Fuel Measured

Fuel 2 h/c = .153

Figure 15

Air/Fuel Computed vs Air/Fuel Measured

Fuel 3 h/c = .1495

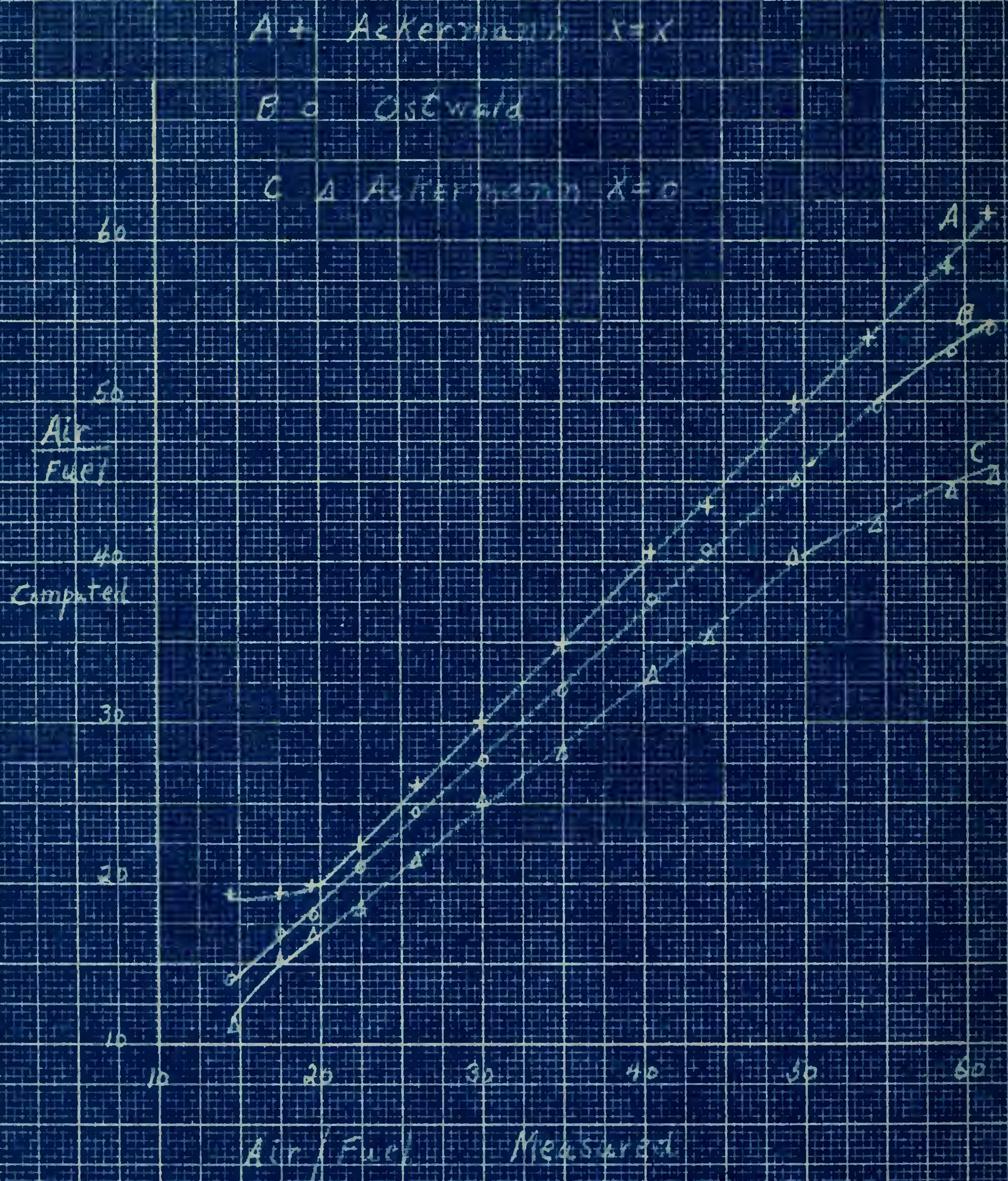


Figure 16

Air/Fuel Computed vs Air/Fuel Measured

Fuel 4 h/c = .134

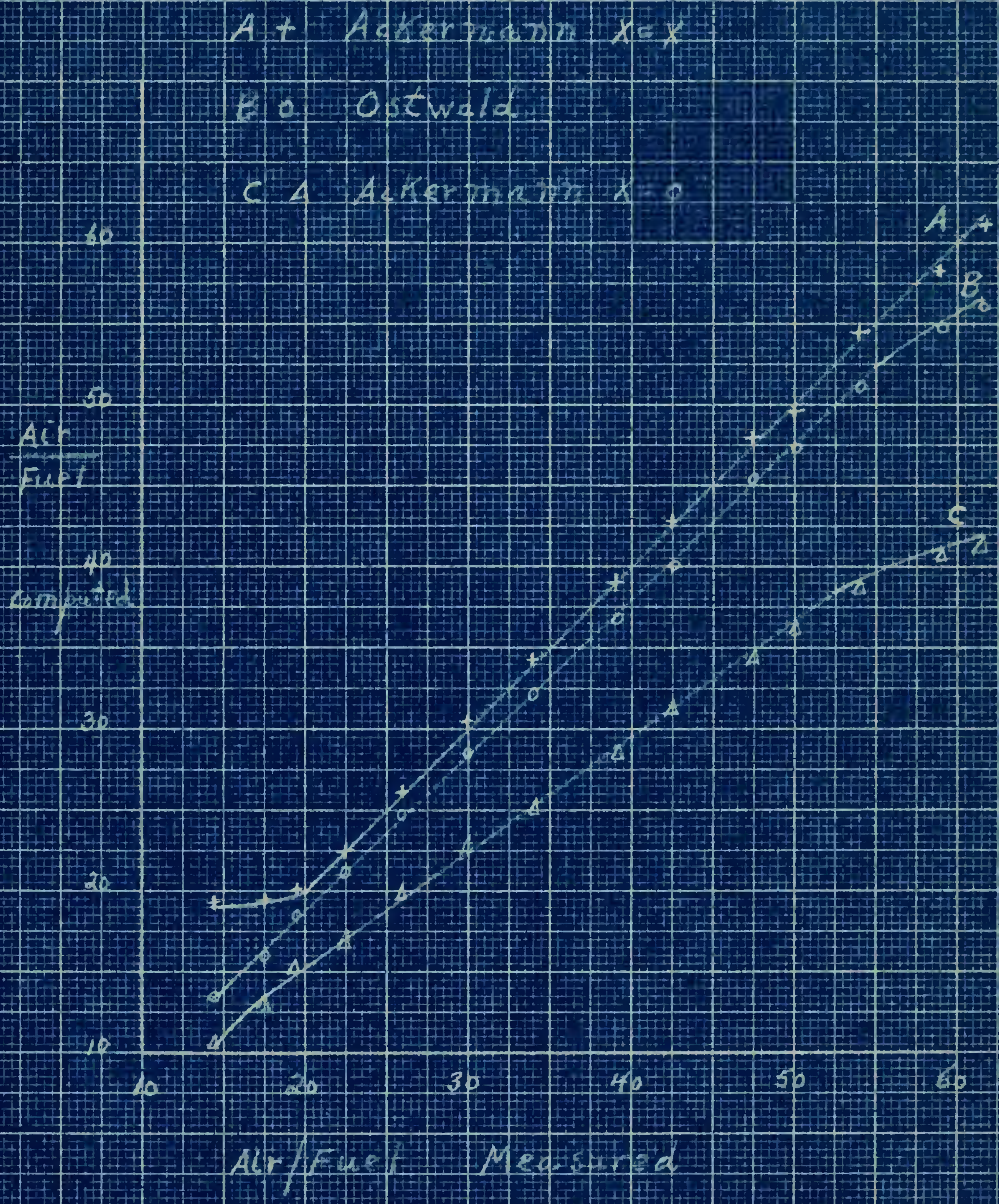


Figure 17

Air/Fuel Computed vs Air/Fuel Measured

Fuel 5 h/c = .129

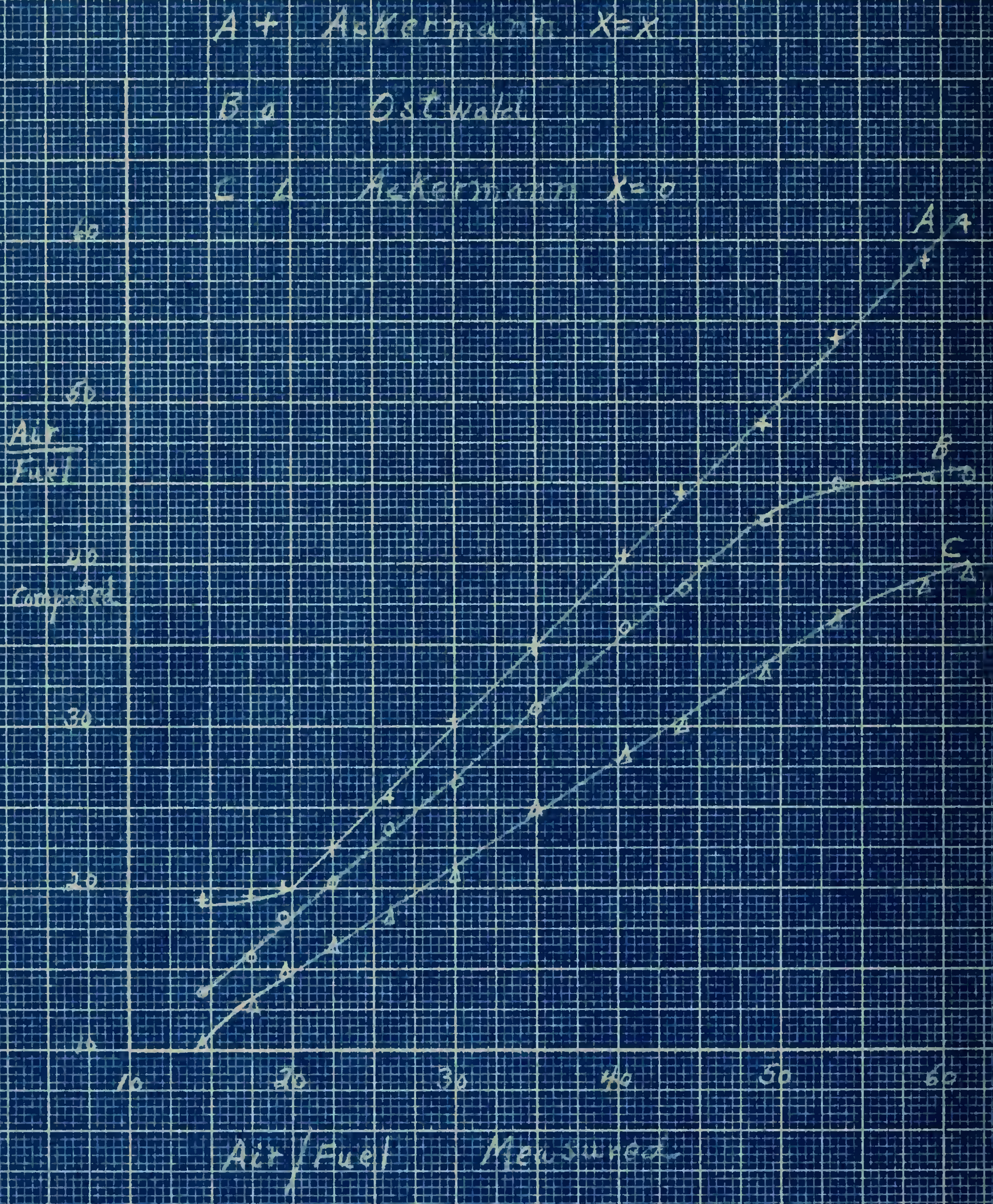


Figure 18

Air/Fuel Computed vs Air/Fuel Measured

Fuel 6 h/c = .1435

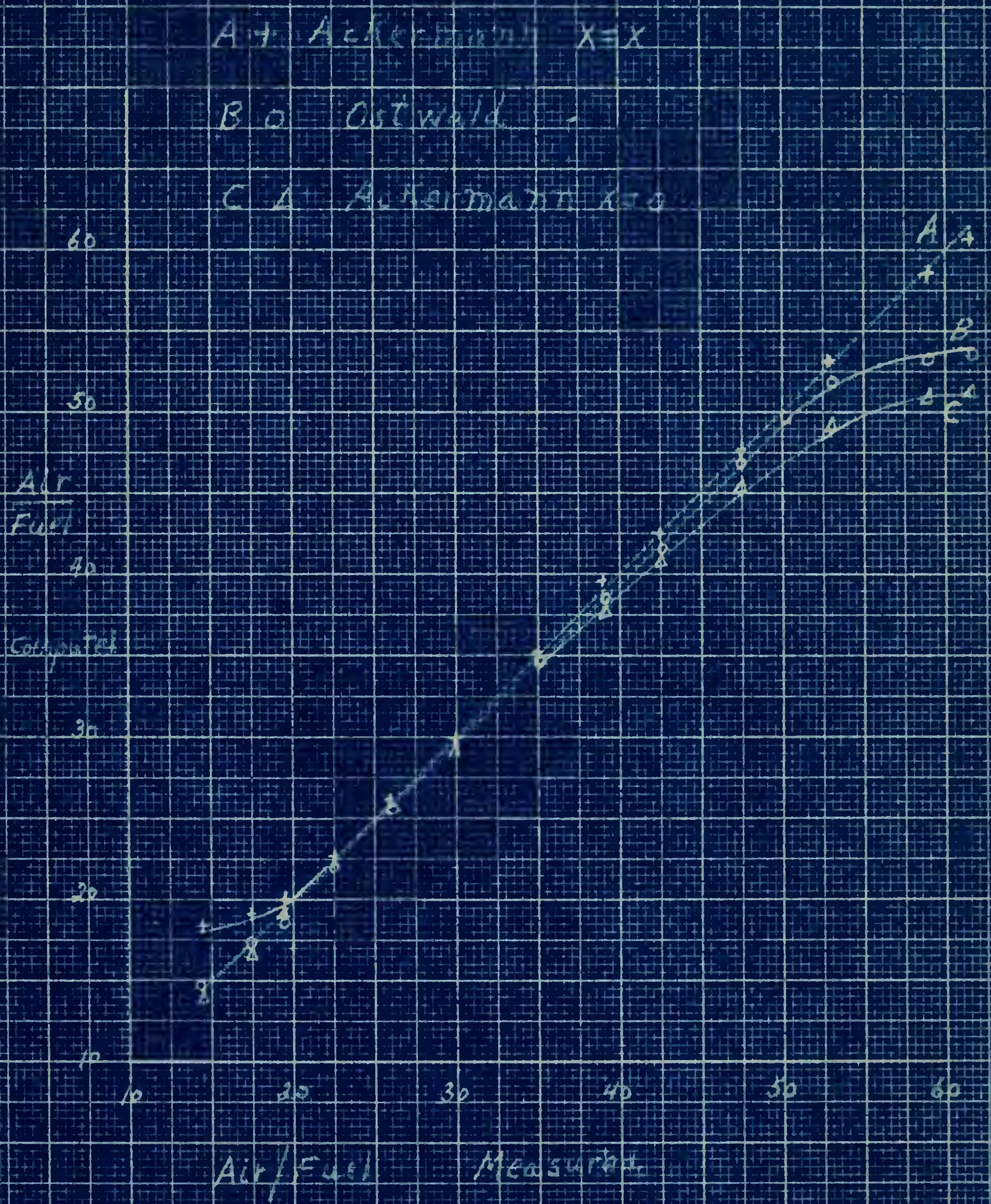


Figure 19

Air/Fuel Computed vs Air/Fuel Measured

Fuel 7 h/c = .172

Fuel 8 h/c = .169

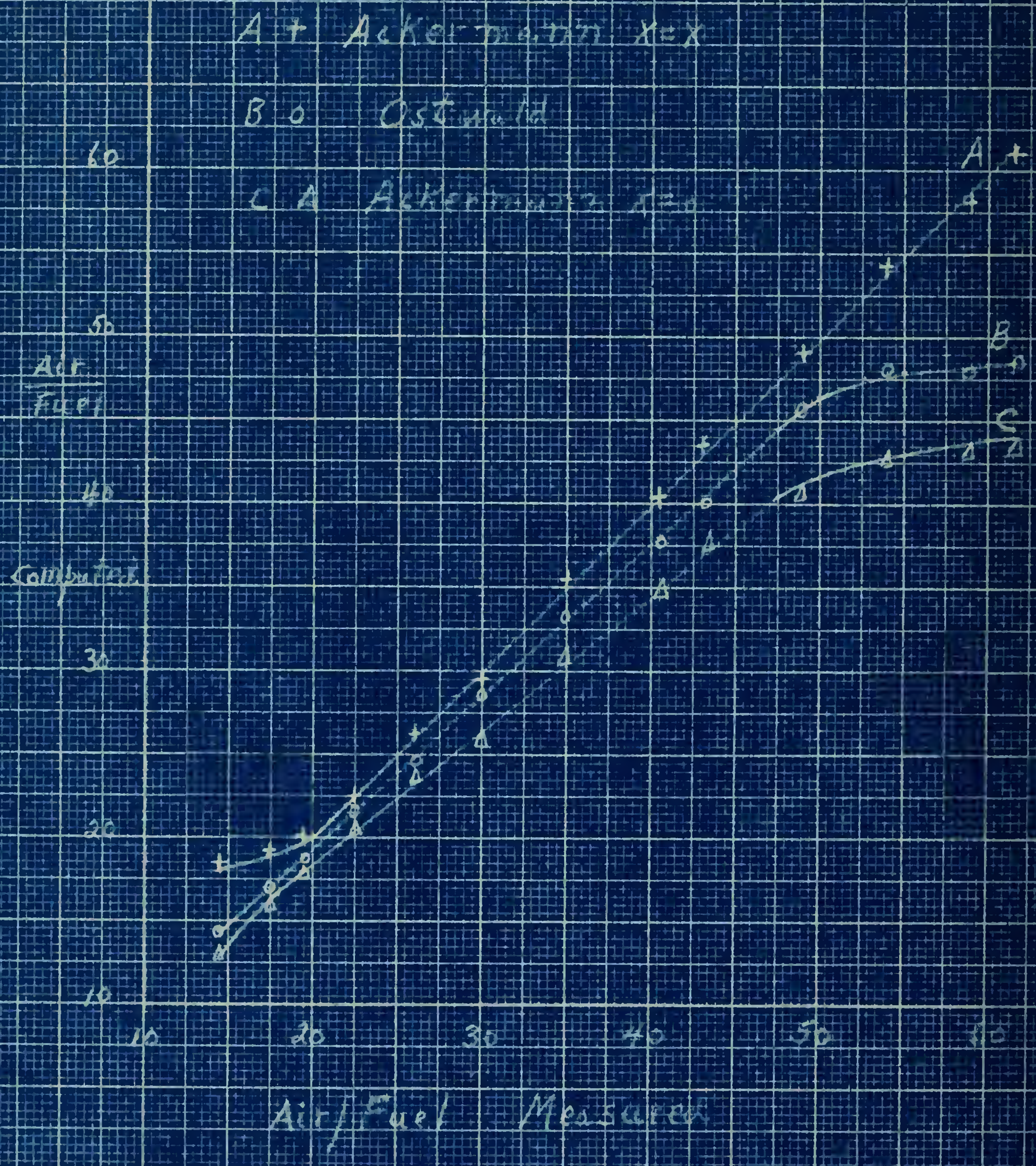


Figure 20

Ackermann Soot X vs Air/Revolution

1300 RPM BMEP 15 lb/sq in

Fuels 4 5 7 8

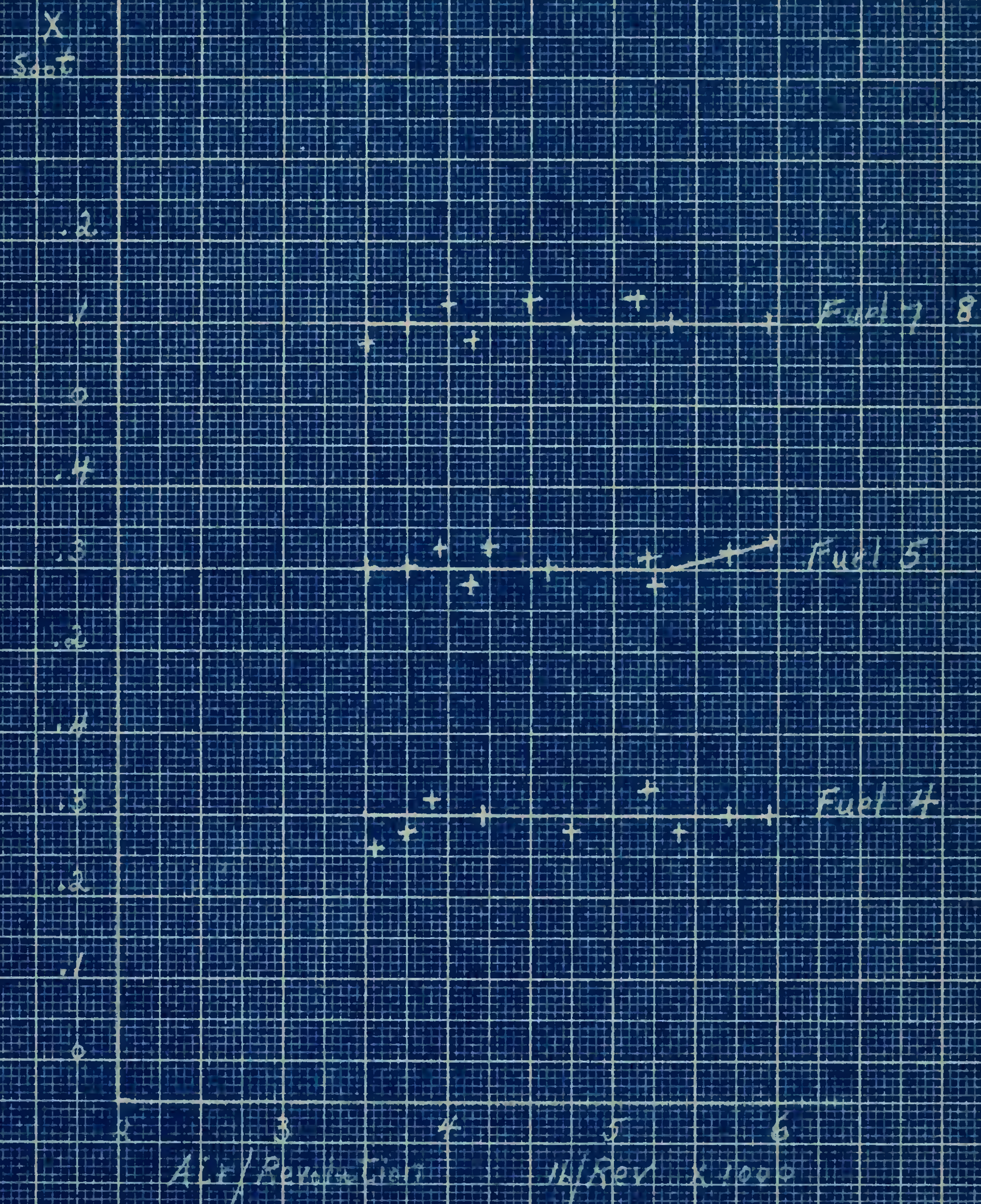
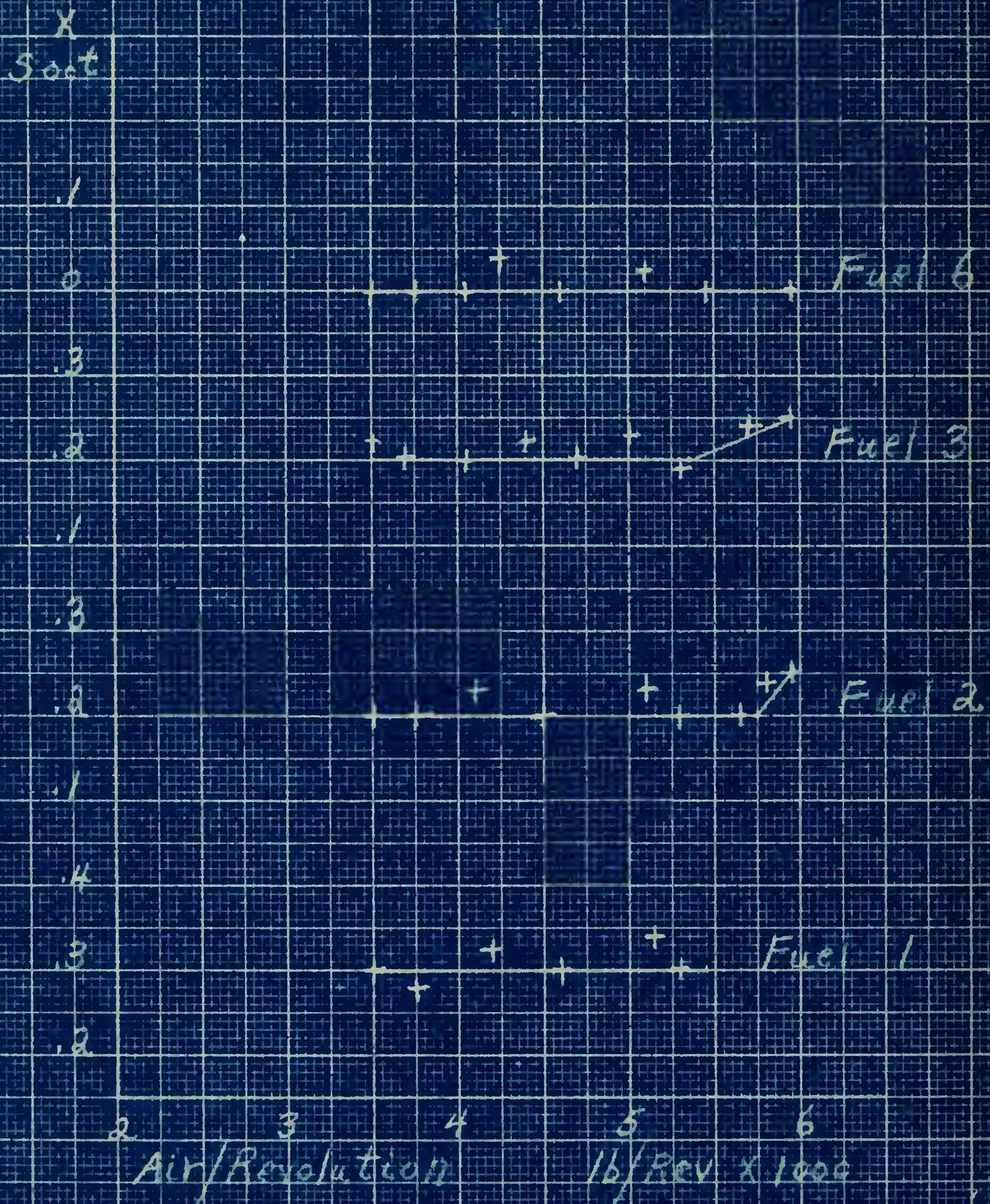


Figure 21

Ackermann Soot X vs Air/Revolution

1300 RPM BMEP 15 lb/sq in

Fuels 1 2 3 6



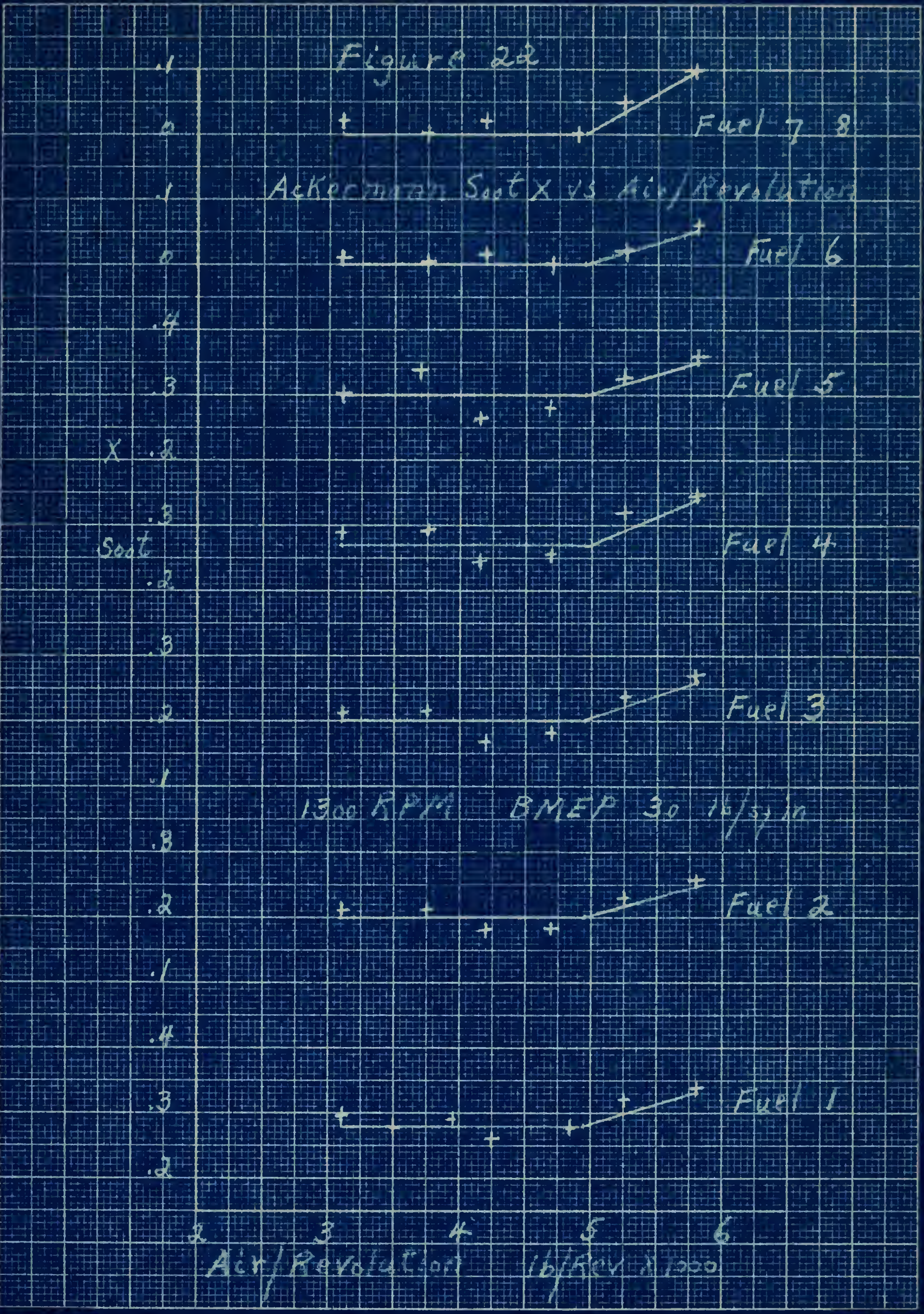


Figure 22

Ackermann Soot X vs Air/Revolution

Figure 23

Ackermann Soot x vs Air/Revolution

1300 RPM BMEP 40 lb/sq in

Fuels 1 2 3 4 5

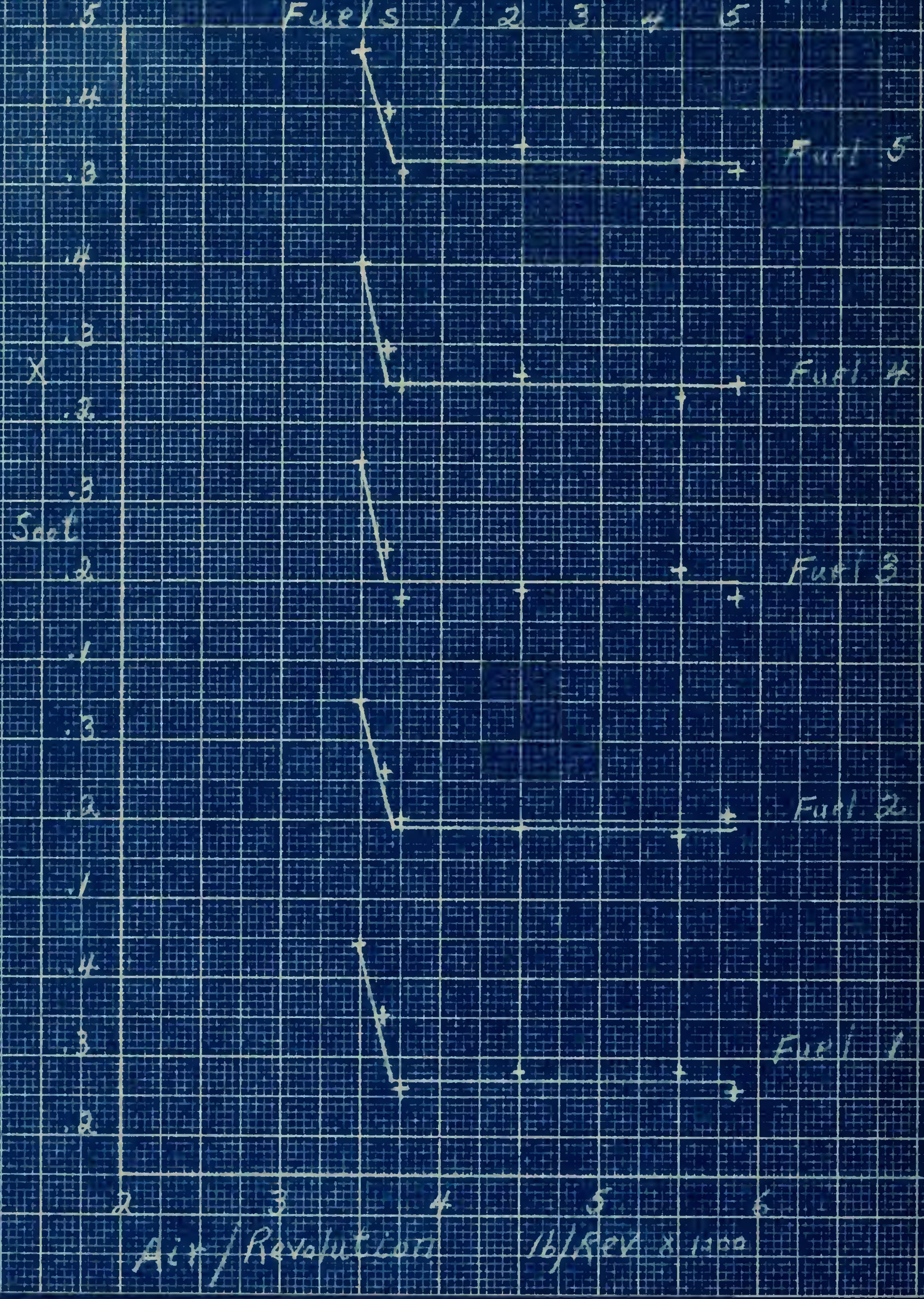


Figure 24

Ackermann Soot x vs Air/Revolution

1300 RPM BMEP 40 lb/sq in

Fuels 6 7 8

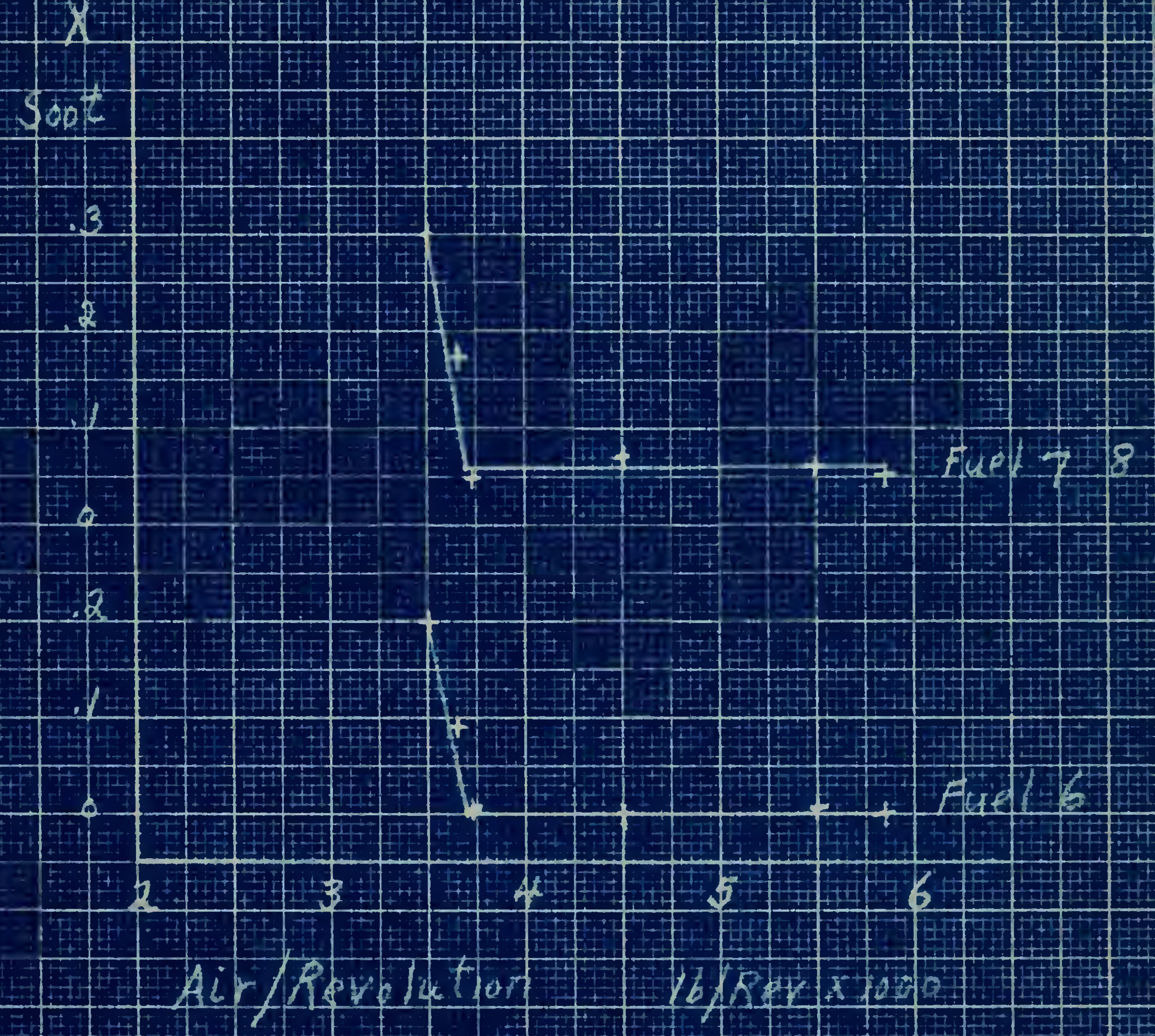


Figure 25

Ackermann Soot X Vs Air/Fuel

Fuels 1 2 3

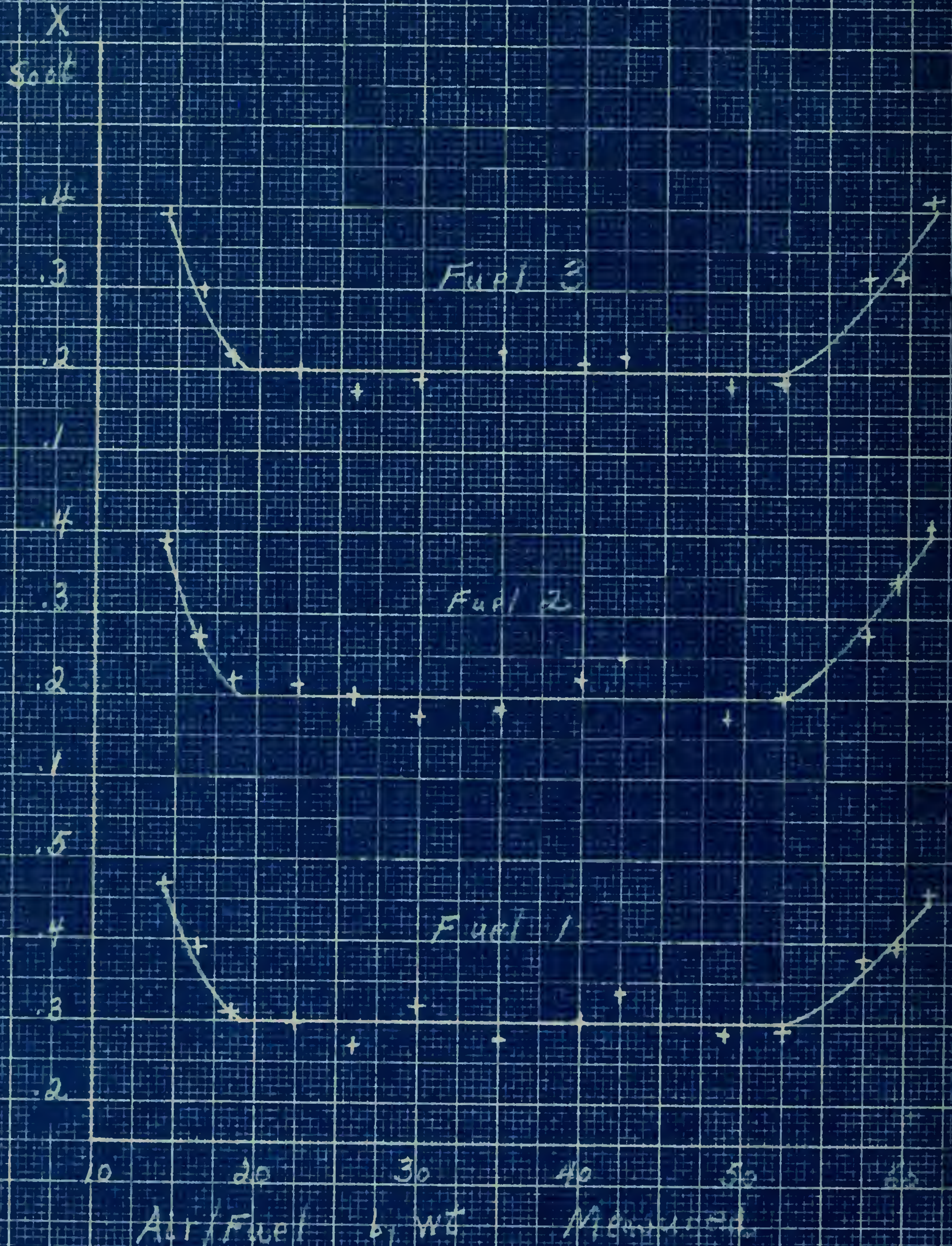


Figure 26

Ackermann Soot X vs Air/Fuel

Fuels 4 5 6 7 8

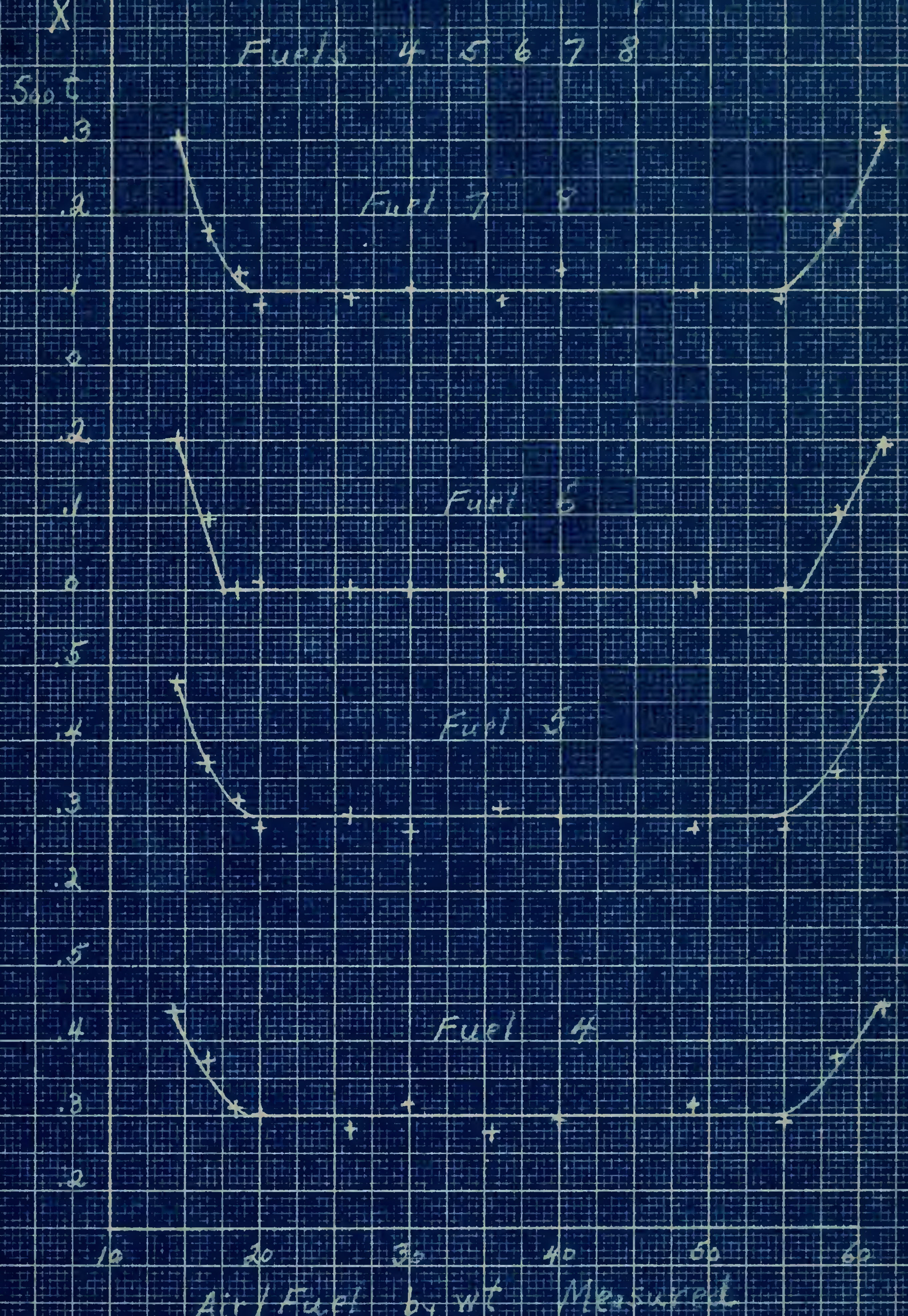


TABLE I

Fuel No.	c	h	n	o	s	$\frac{h}{c}$	$(\frac{A}{F})$ min.	Name	Source of Information
1	.863	.114	.0081	0	.0082	.132	14.22	San Joaquin, Calif. Crude	Int. Critical Tables
2	.85	.13	0	.02	0	.153	14.59	Diesel Fuel	Ackermann
3	.87	.13	0	0	0	.1495	14.54	Diesel Fuel	Maleev
4	.8658	.1161	.0074	0	.0082	.134	14.27	Midway, Calif. Crude	Marks
5	.876	.113	.011	0	0	.129	14.2	California Residuum	Bu.Mines Bulletin 156
6	.863	.167	0	0	.008	.1935	15.3	California Crude	Sterling
7	.853	.147	0	0	0	.172	14.89	Auto-Diesel Fuel	NACA Report 476
8	.855	.145	0	0	0	.169	14.89	Laboratory-Diesel Fuel	NACA Report 476

BIBLIOGRAPHY

a. Ackermann, Dr. Ing. G., München.
"Das Verbrennungsdreieck bei Russbildung" ("The Combustion Triangle at Soot Formation"), *Forshungheft* 366; May-June 1934, p. 1.

b. Gerrish, H. C. and Tessman, A. M.
"Relation of Hydrogen and Methane to Carbon Monoxide in the Exhaust Gases from Internal Combustion Engines," N.A.C.A. Report No. 476. 1934.

c. Maleev, V. L.
"Air-fuel Ratio from Exhaust-gas Analysis of Oil Engines," Bulletin Engineering Experiment Station, Oklahoma A.M. College, vol. 2, no. 5, 1931.

d. Carrier, W. H. and Mackey, C. O.
"Review of Existing Psychrometric Data in Relation to Practical Engineering Problems," A.S.M.E. Trans., vol. 59, nos. 1 and 6; sec. 1, Jan. 1937, pp. 33-47.

e. Zerban, A. H.
"Gas Constant for Humid Air," Heating and Ventilation, vol. 33, no. 12, Dec. 1936, p. 26.

f. Kiefer and Stuart.
"Principles of Engineering Thermodynamics."

g. Loschge, Dr. A.
"Untersuchungen am neuen Lang-Rohölmotor," Dieselmaschinen, V, 1932.

APPENDIX:

Air Measurement Formulas

w = weight of moisture per pound of dry air; grains of moisture per lb. of dry air.

w' = weight of moisture per pound of dry air when saturated at a temperature corresponding to temperature of adiabatic saturation t'; grains of moisture per lb. of dry air.

$t = t_d$ = dry-bulb temperature; °F.

t' = temperature of adiabatic saturation or corrected wet bulb temperature; °F.

t_w = wet bulb temperature, °F.

$t' = t_w + .005(t_d - t_w)$.

r' = latent heat of water vapor.

p_o = Standard Barometric Pressure = 29.92 in. Hg.

$w_o' = w'$ at P_o.

Δp = difference between Observed Barometric Pressure and Standard; in.Hg.

P = Observed Barometric Pressure, in. Hg.

$\Delta p = P - P_o$.

e' = vapor pressure corresponding to the temperature of adiabatic saturation, t'; in. Hg.

$\Delta w'$ = change in w' due to ΔP.

Δw = change in w due to ΔP.

$$w' - w = \frac{(1680 + 0.45w')(t - t')}{r' + 0.45(t - t')}$$

$$\Delta w' = \frac{-w_o'}{1 + \frac{P_o - e'}{\Delta p}}$$

APPENDIX:

Air Measurement Formulas (Cont.)

$$\Delta w = \frac{\Delta w'}{1 + \frac{.45(t-t')}{r'}}$$

or

Approximately; $\Delta w = \dfrac{\Delta w'}{1 + \frac{t-t'}{2300}}$

w_p = grains of moisture per pound of dry air at Barometric Pressure P.

$w_p = w + \Delta w$.

w_p' = Specific Humidity = pounds of moisture per pound of dry air at Barometric Pressure P .

$w_p' = \dfrac{W_p}{7000}$.

w_a = pounds of dry air per pound of mixture at Barometric Pressure P .

$w_a = \dfrac{1}{1 + w_p'}$

R = gas constant for air corresponding to specific humidity, w_p' .

w_a' = pounds of dry air per minute.

d = diameter of orifice, inches = 1.5 inches.

p = pressure drop across orifice, inches H_2O .

t_1 = temperature of air just before orifice, °F.

c = coefficient of discharge = .99 .

APPENDIX:

Air Measurement Formulas (Cont.)

$$w_a' = \frac{\pi 60 x d^2 x c x w_a}{4 x 144} \left[\frac{2g}{R(t_1+460)} x 144(.491P-.0361p) x 144(.0361p)\right]^{\frac{1}{2}}$$

$$w_a' = 30.35 w_a x \left[\frac{p(13.61P-p)}{R(t_1+460)}\right]^{\frac{1}{2}} \qquad \frac{\text{lb. of dry air}}{\text{min.}}$$

APPENDIX:

Fuel Measurement Formulas

v = volume of fuel burette = 195.5 cc.

t_f = temperature of fuel, $^{\circ}F$.

s = specific gravity of fuel at temperature, t_f .

T = time for consumption of 1 burette, min.

F = fuel consumption, $\frac{\text{lb.}}{\text{min.}}$.

$$F = \frac{v \times s}{453.59T} = \frac{195.5\ s}{453.59T} = \frac{.431\ s}{T} \qquad \frac{\text{lb. of fuel}}{\text{min.}}$$

Air to Fuel Ratio:

$$\frac{A}{F} = \frac{w'_a}{F} \qquad \frac{\text{lb. of air}}{\text{lb. of fuel}}$$

Load:

L = load on dynamometer scale, lb.

L' = tare load of dynamometer = 10 lb.

K = dynamometer constant = 4000

N = RPM

$$BHP = \frac{N(L-L')}{K} = \frac{N(L-10)}{4000}$$

$$BHP = \frac{2\ PlAN}{33{,}000}\ ; \quad BMEP = \frac{33{,}000\ BHP}{2\ lAN}$$

l = stroke = 5.5 inch.

A = area = $\frac{\pi}{4}d^2$; d = 4.5 inch.

APPENDIX:

Fuel Measurement Formulas (Cont.)

$$BMEP = \frac{N(L-10)}{4000} \times \frac{33,000}{2N} \times \frac{12 \times 4}{5.5 \times 4.5^2 \pi}$$

$$BMEP = .565(L-10) \qquad lb/in^2.$$

$$\text{Spec. Fuel Consumption} = \frac{F \times 60}{BHP} \; ; \; \frac{lb.}{BHP.hr.}$$

APPENDIX:

Ackermann Combustion Triangle Formulas

c = carbon; part by weight in 1 pound of fuel

h = hydrogen; part by weight in 1 pound of fuel

o = oxygen; part by weight in 1 pound of fuel

n = nitrogen; part by weight in 1 pound of fuel

s = sulfur; part by weight in 1 pound of fuel

M = molar volume at any normal condition

For complete combustion of 1 pound of fuel with minimum oxygen.

$$c\,lb\,C + h\,lb\,H + s\,lb\,S + n\,lb\,N + M\left(\frac{c}{12} + \frac{h}{4} + \frac{s}{32}\right)ft^3 O_2 =$$

$$M\left(\frac{c}{12}ft^3 CO_2 + \frac{h}{2}ft^3 H_2O + \frac{s}{32}ft^3 SO_2 + \frac{n}{28}ft^3 N_2\right) \qquad (1)$$

Assume SO_2 formed by combustion absorbed in liquid of analysis apparatus.

Assume soot and not CO formed by incomplete combustion.

CO_2 = % by volume of CO_2 in exhaust gases

O_2 = % by volume of O_2 in exhaust gases

N_2 = % by volume of N_2 in exhaust gases

$$CO_2 + O_2 + N_2 = 1 \qquad (2)$$

Oxygen consumed for formation of CO_2 = volume of CO_2 .

Volume of water vapor formed by combustion = H_2O .

$$\frac{H_2O}{CO_2} = \frac{h/2}{c/12} \quad ; \quad H_2O = 6\,\frac{h}{c}\,CO_2$$

APPENDIX:

Ackermann Combustion Triangle Formulas

Oxygen consumed for formation of $H_2O = 3\,\frac{h}{c}\,CO_2$.

Likewise, oxygen consumed for combustion of sulfur $= \frac{3}{8}\,\frac{s}{c}\,CO_2$.

For complete combustion; in 1 ft^3 of dry exhaust gases

total oxygen in combustion products + free oxygen =

$$(1 + 3\,\frac{h}{c} + \frac{3}{8}\,\frac{s}{c})CO_2 + O_2 \qquad (3)$$

N_2' = nitrogen supplied by fuel .

$$\frac{N_2'}{CO_2} = \frac{n/28}{c/12} \;; \qquad N_2' = \frac{3}{7}\,\frac{n}{c}\,CO_2 \,.$$

Nitrogen supplied by air = nitrogen in exhaust gases - nitrogen supplied by fuel.

Nitrogen supplied by air $= N_2 - N_2'$.

Oxygen supplied by air for combustion measured by nitrogen supplied by air.

$$\text{Oxygen supplied by air} = \frac{21}{79}(N_2 - N_2') = \frac{21}{79}(N_2 - \frac{3}{7}\,\frac{n}{c}\,CO_2) \qquad (4)$$

Oxygen supplied by fuel $= O_2'$.

$$\frac{O_2'}{CO_2} = \frac{o/32}{c/12} \;; \qquad O_2' = \frac{3}{8}\,\frac{o}{c}\,CO_2 \,.$$

Therefore, for complete combustion; for 1 ft^3 dry exhaust gases

$$\text{Total oxygen} = \frac{21}{79}(N_2 - N_2') + O_2' = \frac{21}{79}(N_2 - \frac{3}{7}\,\frac{n}{c}\,CO_2) + \frac{3}{8}\,\frac{o}{c}\,CO_2 \qquad (5)$$

APPENDIX:

Ackermann Combustion Triangle Formulas (Cont.)

Equation (3) = Equation (5)

Eliminate N_2 by Equation (2)

Therefore,

$$\left[4.76 + \frac{3}{7}\frac{n}{c} + 3.76\left(3\,\frac{h}{c} + \frac{3}{8}\frac{s}{c} - \frac{3}{8}\frac{o}{c}\right)\right]CO_2 = 1 - 4.76\ O_2 \qquad (6)$$

Let O_2 be abscissa and CO_2 be the ordinate of rectangular coordinates.

Equation (6) is equation of hypotenuse of combustion triangle.

No measured pair of CO_2 and O_2 can lie outside of triangle.

For incomplete combustion, point corresponding to CO_2 and O_2 as measured lies inside triangle.

Incomplete combustion; assume soot only and not CO formed.

Assume soot is pure carbon.

x = measure of soot formed

x = fraction of c in one pound of fuel which does not burn

Unburned carbon for 1 pound of fuel = xc

Burned carbon for 1 pound of fuel = (1-x)c

Therefore, substitute in equation (6) (1-x)c for c.

$$\frac{1}{(1-x)c}\left[4.76(1-x)c + \frac{3}{7}\,n + 3.76\left(3h + \frac{3}{8}\,s - \frac{3}{8}\,o\right)\right]CO_2 = 1 - 4.76\ O_2 \qquad (7)$$

For x = constant, equation (7) represents a linear relation between CO_2 and O_2.

APPENDIX:

Ackermann Combustion Triangle Formulas (Cont.)

For various values of x, equation (7) gives a family of straight lines all passing through $CO_2 = o$ and $O_2 = .21$.

For x = o, equation (7) becomes equation (6) and represents hypotenuse of combustion triangle.

For x = 1, equation (7) represents the O_2 a xis, the abscissa.

Thus, the amount of unburned carbon, x, can be found corresponding to any measured values of CO_2 and O_2 in exhaust gases.

Equation (7) will not hold if fuel is pure carbon.

Let e = excess air factor.

$$e = \frac{\text{Actual air supplied}}{\text{Minimum air for complete combustion}}$$

$$\frac{\text{pound of fuel}}{1\ \text{ft}^3\ \text{of dry exhaust gases}} = \frac{12}{M(1-x)c}\,CO_2 \qquad (8)$$

$$\text{Minimum air for 1 pound of fuel} = \frac{1}{.21}\,M\left(\frac{c}{12} + \frac{h}{4} + \frac{s}{32} - \frac{o}{32}\right).$$

Therefore for each ft^3 of dry exhaust gases

$$\text{Minimum air} = L_{min.} = \frac{1}{.21}\left(\frac{c}{12} + \frac{h}{4} + \frac{s}{32} - \frac{o}{32}\right)\frac{12}{(1-x)c}\,CO_2 \qquad (9)$$

$$\text{Actual air} = L_{act} = \frac{1}{.79}\left(1 - CO_2 - O_2 - \frac{3}{7}\,\frac{n}{(1-x)c}\,CO_2\right) \qquad (10)$$

Therefore

$$e = \frac{L_{act}}{L_{min.}} = \frac{\frac{21}{79}\left(1 - CO_2 - O_2 - \frac{3}{7}\,\frac{n}{(1-x)c}\,CO_2\right)(1-x)}{\left(1 + 3\,\frac{h}{c} + \frac{3}{8}\,\frac{s}{c} - \frac{3}{8}\,\frac{o}{c}\right)CO_2} \qquad (11)$$

APPENDIX:

Ackermann Combustion Triangle Formulas (Cont.)

Eliminate (1-x) in equation (11) by equation (7)

$$e = \frac{1 - CO_2 - O_2}{1 - 4.76(CO_2+O_2)} \left[\frac{\frac{21}{79}\cdot\frac{3}{7}n+3h+\frac{3}{8}s-\frac{3}{8}o}{c+3h+\frac{3}{8}s-\frac{3}{8}o} \right] - \frac{\frac{21}{79}\cdot\frac{3}{7}n}{c+3h+\frac{3}{8}s-\frac{3}{8}o} \qquad (12)$$

Let $a = \dfrac{\frac{21}{79}\cdot\frac{3}{7}n + 3h + \frac{3}{8}s - \frac{3}{8}o}{c + 3h + \frac{3}{8}s - \frac{3}{8}o}$

and

$$b = \frac{\frac{21}{79}\cdot\frac{3}{7}n}{c + 3h + \frac{3}{8}s - \frac{3}{8}o}$$

Then equation (12) becomes

$$CO_2 = \frac{a - b - e}{a - 4.76(b+e)} - O_2 \qquad (13)$$

For $\frac{1}{e}$ = constant; equation (13) gives a linear relationship between CO_2 and O_2.

For various values of $\frac{1}{e}$, equation (13) gives a family of straight lines making an angle of 45° with CO_2 and O_2 axis.

APPENDIX:

Ostwald Combustion Triangle Formulas

Let c = carbon in 1 pound of fuel

h = hydrogen in 1 pound of fuel

$K = \frac{h}{c}$

CO_2 = % by volume of CO_2 in exhaust gases

CO = % by volume of CO in exhaust gases

CH_4 = % by volume of CH_4 in exhaust gases

N_2 = % by volume of N_2 in exhaust gases

H_2O = % by volumes of H_2O in exhaust gases

O_2 = excess oxygen

O_2' = oxygen consumed

e = excess air factor

$$e = \frac{O_2 \text{ present}}{O_2 \text{ required for complete combustion}}$$

$$c = 12(CO_2 + CO + CH_4)$$

$$h = 2.016(H_2 + H_2O + 2CH_4)$$

$$K = \frac{2.016(H_2 + H_2O + 2CH_4)}{12(CO_2 + CO + CH_4)} \qquad (1)$$

$$H_2O = 5.955K(CO_2 + CO + CH_4) - H_2 - 2CH_4 \qquad (2)$$

$$N_2 = \frac{79.1}{20.9}(O_2 + O_2') \qquad (3)$$

$$O_2' = CO_2 + \frac{1}{2}CO + \frac{1}{2}H_2O \qquad (4)$$

Substitute H_2O from (2) in (4)

Substitute O_2' from (4) in (3)

APPENDIX:

Ostwald Combustion Triangle Formulas (Cont.)

Then

$$N_2 = 3.785\ O_2 + 3{,}785\ CO_2 + 1.892\ CO - 1.892\ H_2 - 3.785\ CH_4 + 11.268\ K\ (CO_2 + CO + CH_4) \qquad (5)$$

But

$$N_2 = 100 - O_2 - CO_2 - CO - H_2 - CH_4 \qquad (6)$$

Equation (5) = Equation (6) .

$$O_2 + CO_2(1 + 2.355K) + CO(0.604 + 2.355K) - 0.186\ H_2 - CH_4(0.582 - 2.355K) = 20.9 \qquad (7)$$

$$\frac{1}{e} = \frac{CO_2 + CO + \frac{1}{2} H_2 + \frac{1}{2} H_2O + 2CH_4}{O_2 + CO_2 + \frac{1}{2} CO + \frac{1}{2} H_2O} \qquad (8)$$

Substitute H_2O from equation (2) in equation (8) .

$$\frac{1}{e} = \frac{(1+2.977K)(CO_2+CO+CH_4)}{[O_2+CO_2(1+2.977K)+CO(.5+2.977K)-CH_4(1-2.977K)-\frac{1}{2}H_2]} \qquad (9)$$

Assume, $CH_4 = .22$; $H_2 = .51\ CO$

Then equation (7) becomes,

$$O_2 + CO_2(1 + 2.355K) + CO(.509 + 2.355K) = 21.028 - .518K \qquad (10)$$

And equation (9) becomes

$$\frac{1}{e} = \frac{(1+2.977K)(CO_2+CO+.22)}{[O_2+CO_2(1+2.977K)+CO(.245+2.977K)-.22+.655K]} \qquad (11)$$

APPENDIX:

$\frac{\text{Air}}{\text{Fuel}}$ Ratio

Theoretical Air to Fuel Ratio Minimum for Complete Combustion

$= (\frac{A}{F})$ min.

$$(\frac{A}{F})_{\text{min.}} = \frac{11.53(1 + 3\frac{h}{c})}{1 + \frac{h}{c}}$$

Ackermann Triangle

Actual Air to Fuel Ratio Supplied to Engine = $(\frac{A}{F})_{\text{Act}}$

$$(\frac{A}{F})_{\text{Act}} = \frac{e}{(1-x)} (\frac{A}{F})_{\text{min.}}$$

where e and x correspond to CO_2 and O_2 found by exhaust analysis.

Ostwald Triangle

$$(\frac{A}{F})_{\text{Act}} = e\ (\frac{A}{F})_{\text{min.}}$$

where e corresponds to CO_2 and O_2 found by exhaust analysis.

The
R2

Thesis 6317
R2 Ramsbotham
Composition of exhaust gases of solid injection pre-combustion chamber Diesel engine with reduced air charge.

Thesis 6317
R2 Ramsbotham
Composition of exhaust gases of solid injection pre-combustion chamber Diesel engine with reduced air charge.

thesR2
Composition of exhaust gases of solid in
3 2768 002 05274 8
DUDLEY KNOX LIBRARY